TECHNICAL SERVICE CENTER
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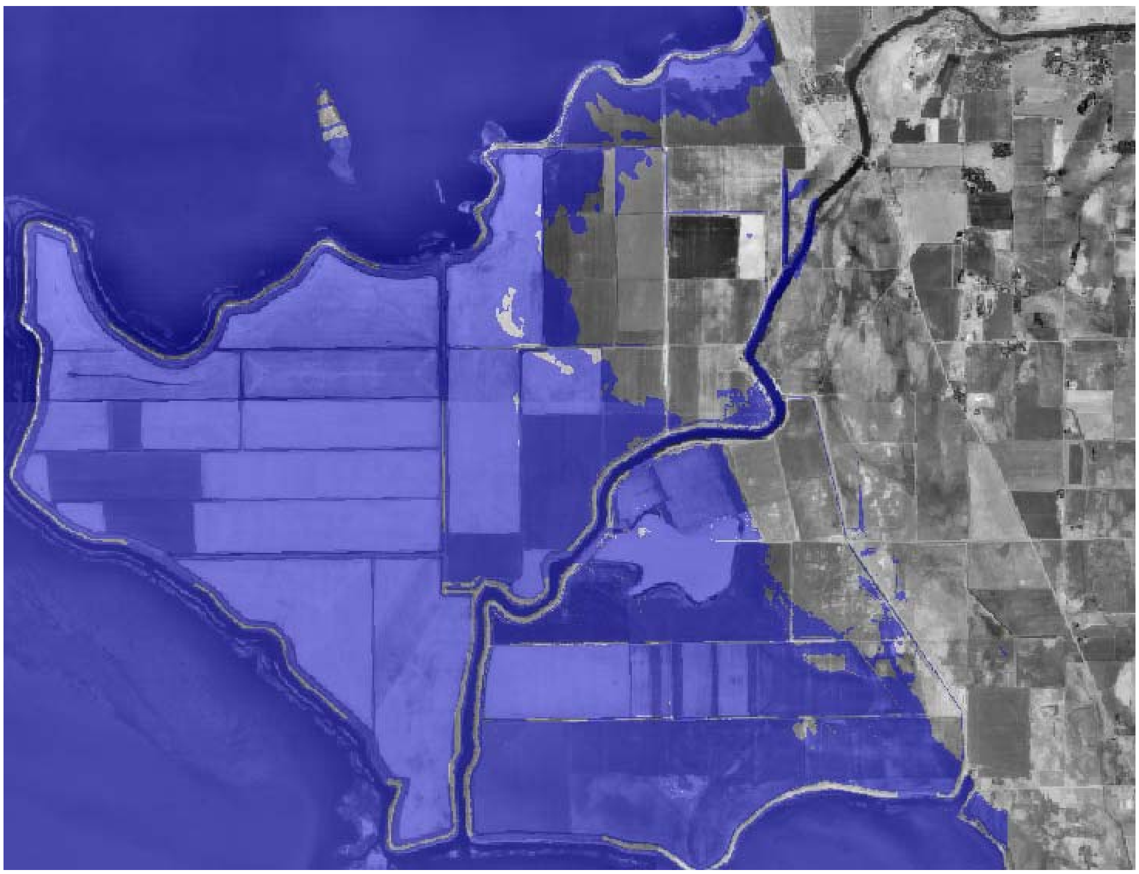
Lower Williamson River
Floodplain and Delta Restoration: Hydraulic Modeling



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Lower Williamson River
Floodplain and Delta Restoration: Hydraulic Modeling

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1.0 Introduction

The Williamson River is located in southern Oregon north of Klamath Falls, where it terminates in Upper Klamath Lake. The river drains a basin of about 3000 square miles, and is the largest source of inflow to Upper Klamath Lake. The Williamson River Restoration Project is located along the lower 4 miles of the river as it joins Upper Klamath Lake. Historically the river was highly sinuous in the lower reach and the floodplain/delta adjacent to this part of river was primarily wetlands. This is evident on aerial photographs from as recent as the 1940's. Some time after the 1940's the river was dredged and parts of the river were straightened to facilitate navigation; levees were constructed along both sides of the river, along the lakeshore, and at various other locations in the floodplain/delta in order to control flooding and reclaim the land for agriculture. These changes altered the river plan form, significantly changed channel hydraulic characteristics, and cut off the connection with the floodplain/delta.

The Nature Conservancy (TNC) is the current owner of the land surrounding the lower Williamson River. TNC has initiated restoration planning on the historic floodplain/delta with the goal of restoring and maintaining, to the greatest extent practical, the natural ecological processes and functions of the lower river and floodplain/delta. The restoration focuses on providing habitat essential to the survival of Lost River and shortnose suckers, two endangered fish species that historically used the emergent wetlands of the floodplain/delta. The use of the term "floodplain/delta" is adopted in this report as referring to overbank areas surrounding the Williamson River incorporating TNC's land, including the former Tulana Farms, to the north and west of the river, and the former Goose Bay Farms, to the south and east of the river (see figure 5). This usage is to denote the fact that the distinction between a true floodplain and a delta in this area is highly dependent on the water surface elevation of Upper Klamath Lake. At high lake elevations, the overbank areas along most of the study reach will be more like a delta, being submerged even in the absence of overbank flow from the river. However, at low lake elevations, much of the overbank area is not submerged and overbank flow into these areas resembles processes that occur for a river with a true floodplain. Instead of arbitrarily designating one section floodplain and another delta, the term "floodplain/delta" is used to refer to the entire study area.

Potential restoration designs include breaching of river and lakeshore levees and potential modifications to the existing river channel (alignment, width and depth) to restore natural processes and functions of the natural river channel. The purpose of this study is to determine strategic locations for levee breaches along the Williamson River so that water will overflow the banks of the river and flow onto the floodplain/delta. Additionally, river flow that gets into Goose Bay and Tulana will have to make its way into Upper Klamath Lake. Therefore it is necessary to determine strategic locations for levee breaches along the shoreline of Goose Bay and Tulana, and at interior levees in Goose Bay. It is also vital to determine, once levees are breached, if changes to the current channel geometry are necessary to allow flow to get onto the floodplain/delta. Furthermore, it must be determined if potential alterations to the river channel and levees in the Williamson River will increase flood stage upstream of the study area.

1.1 Study Objectives

The objectives of this study are to determine feasible methods—by the strategic breaching of river, shoreline, and interior levees—of restoring the hydraulic connection between the river channel and floodplain/delta and other natural characteristics of the river channel such as width, depth, and alignment or sinuosity. Specifically, the following questions are addressed as part of this study:

1.2 Study Questions

- *Where can the levees be strategically breached to closely match the flow patterns of the case without any levees?*

  The approach taken here is to determine the hydraulic properties of the river and floodplain as if river, shoreline, and interior levees were not present in the study area. This approach will allow for a determination of dominant flow areas within the floodplain/delta, and for the determination of the best locations to breach levees so that the dominant flow patterns may be closely matched. This will restore the hydraulic connection between the river, floodplain/delta, and lake with a minimum amount of work. Additionally, the natural flow patterns will allow for a more natural succession of vegetation in the floodplain/delta. Thus, the answer to the above question will provide much valuable information on restoring the hydraulics of the study area.

- *Are channel alterations necessary to cause the 1.5-year flood to spill overbank and onto the floodplain/delta?*

  The 1.5 year flood is a flow rate that is equaled or exceeded in 2 out of every 3 years on average. This flow rate is often equated with the bankfull discharge for many natural river channels (Leopold, 1994). The bankfull discharge is the flow rate that is fully contained within the river channel, but for which increases in river flow will begin to inundate the floodplain. For the Williamson River, the 1.5 year flood peak is 2,070 cubic feet per second (ft^3/s). The concept of the bankfull discharge is only applicable to the floodplain upstream from the delta of Upper Klamath Lake. In contrast, the delta is inundated during periods of high lake elevation, regardless of river flow.

- *What are the potential benefits to channel alterations such as restoring channel alignment and geometry?*

  There is a desire to restore the river to its historic, or pre-development, channel alignment, or to the alignment shown in plat maps and aerial photographs dating back to the late 19th century. However, there have been alterations and changes to the river and floodplain/delta that will make it difficult to fully restore the river to its pre-development condition (see section 5.1). The analysis will evaluate the hydraulic benefits of restoring features of the historic channel alignment, including reconnecting the historic oxbow and reopening an historic channel at the river mouth.

- *Do any of the modeled scenarios increase upstream flood stage?*

  An important concern is whether or not alterations done to the channel, either in the form of alterations of channel geometry or by levee breaching, will have the effect of increasing the upstream flood stage. In order for a management action to be feasible, any alterations to the study area, including levee breaching, should not increase the upstream flood stage.

The questions posed in this study specifically address restoration of a hydraulic connection between the river and the floodplain/delta, and the potential for restoration of the river channel alignment within the river floodplain/delta system. The results obtained in this study can be applied to the existing conditions in the study area. It is beyond the scope of this study to assess the effects of wind and temperature gradients on flow patterns in Agency Lake, Upper Klamath Lake, and in newly created lake habitat resulting from potential levee breaches (such as on the Tulana side of the river). The results of this study are indicative of flow patterns that arise as a result of strategic levee breaches, and the river and lake topography of the study area.

2.0 Background

There have been no modeling investigations of the entire lower Williamson River floodplain/delta system that include the river, Upper Klamath Lake, and Agency Lake. Philip Williams & Associates (PWA) (2000) utilized the DHI Water & Environment Mike 11, one-dimensional hydrodynamic flow model to simulate the seasonal variations of river flow and lake elevations within the lower Williamson River and on the north (Tulana) side of the delta/floodplain. PWA used the hydrodynamic modeling to evaluate the sensitivity of the river system to channel narrowing as a potential restoration element. Model results showed that average channel velocities are not significantly increased in the narrowed channel relative to the existing conditions because the lower part of the Williamson River is heavily influenced by the backwater from Upper Klamath Lake. They concluded that restoration actions designed to restore flow complexity and increase flow velocities will need to involve raising the channel bed as well as narrowing the channel.

PWA also used the model to compare the flow exchange between the river and the delta/floodplain for historic and current channel conditions. Historic conditions were simulated by modifying the existing channel conditions based on topographic information from the 1916 plat maps, as well as by narrowing the channel by 20 to 30%. Current channel conditions were simulated using the existing channel, but assuming all the levees were removed. PWA simulated a ten-year period from 1960 to 1969. Model simulations showed that the flow volume exchange between the river and the delta/floodplain under the current channel conditions is much less than under the simulated historic channel conditions. According to PWA, the results of the flow volume exchange analysis indicate that removal of the levees alone is not sufficient to restore the hydraulic connection between the river channel and delta/floodplain because the existing river channel is too large, and can convey the majority of the river flows. They recommended that levee removal or breaching be done in conjunction with the restoration of a smaller river channel, either by reducing the size of the existing channel alignment, or re-meandering a new reach of a smaller channel across the delta/floodplain.

PWA (2001) also performed hydrodynamic, sediment transport, and water quality modeling of Agency and Upper Klamath Lakes using the DHI Water & Environment models MIKE11, MIKE21, and MIKE3 (http://www.dhisoftware.com), but this did not include modeling of the Williamson River and the floodplain/delta. The PWA modeling effort shows that flow in Upper Klamath Lake is variable, and that flow around the shoreline of the floodplain/delta and Upper Klamath Lake can occur in either direction (westward or eastward). Other than this, the results of the PWA work are not applicable to this study.

Graham Matthews and Associates (2001) modeled flow in the Williamson River as part of an evaluation of the Riverbend early action project. HEC-RAS, a one-dimensional steady state hydraulic model was developed for pre and post project conditions of the Williamson River from the confluence of Upper Klamath Lake to approximately 2,600 ft upstream of restoration project site. The one-dimensional model was used to determine water surface elevations, average channel velocities, friction slope, and other hydraulic parameters within the project reach. RMA2, a two-dimensional hydrodynamic model was also applied to model pre and post project conditions within the restoration site only. The two-dimensional model was used to analyze spatial variations in flow velocity within the channel (pre and post project) and newly created overbank wetland areas (post project) over a range of discharges and lake elevations. The project area is upstream of any potential additional levee breaches and river channel alterations being looked at here, and there is not thought to be any interaction or effects from the Riverbend site on the potential alterations examined in this study. Therefore, the investigation carried out here is independent of the work completed by Graham Matthews & Associates (2001).

Other investigations of the lower Williamson River focused on the following topics:

- changes in channel geometry over the past several years (Graham Matthews & Associates, 2002a),
- riverbed substrate and changes in sediment composition over the past several years (Graham Matthews & Associates, 2002b), and
- the potential impacts of the release of the sediment stored behind Chiloquin Dam on the Sprague and Williamson Rivers in the event of dam removal (Randle and Daraio, 2003).

The Graham Matthews & Associates (2002a) study showed that relatively small geometric changes to the river channel occurred in the lower Williamson River from 1996 to 2001, even though there was a very large flood event in January, 1997. However, there was a net reduction in cross sectional area in this same time period at locations just upstream of the oxbow indicating that some deposition is occurring. The substrate investigation (Graham Matthews & Associates, 2002b) revealed only minor changes in particle size distributions along the lower Williamson River over the same time period. The investigation by Randle and Daraio (2003) showed that the potential release of 61,000 tons of sediment, from behind Chiloquin Dam, would have a minor effect on the geometry of the river. The primary effect would be to increase the bed surface elevations of the river by a few feet at some locations. However, given the depth of the channel, the effects on the hydraulics of the river likely would be negligible.

3.0 Historic Hydrologic Conditions

Since 1919, regulation of Upper Klamath Lake has been controlled by the Link River Diversion Dam located at the downstream end of the lake. This dam is operated by the Bureau of Reclamation as part of an irrigation and hydropower project. Figure 1 shows the average daily lake surface elevations for a complete water year, based on the 30 years of record from 1970 to 2000. Figure 1 also shows the lake elevations for the 2002 water year and the lake elevations for part of the 2003 water year. Lake water surface elevations are lowest in October and early November and reach the highest levels of the year by March or April.

The U.S. Geological Survey (USGS) operates a stream gage on the Williamson River approximately 10 miles upstream of Upper Klamath Lake and downstream of its confluence with the Sprague River. The total drainage area upstream from this gage is approximately 3,000 square miles, which includes the drainage area of the Sprague River basin. The study reach of the lower Williamson River extends approximately 5 miles upstream from the mouth of the river at Upper Klamath Lake to the Modoc Point Road Bridge. The average slope of this mild reach is 0.0003. The river channel width ranges from 170 to 300 feet, and the flow depth ranges from 10 to 18 feet depending on the water surface elevation of Upper Klamath Lake, which typically varies between 4138 and 4143 feet.

The Williamson River represents approximately 50% of the flow into Upper Klamath Lake. Approximately 18% of the flow into Upper Klamath Lake is from Agency Lake, which flows through the straits on the west side of the property, adjacent to Tulana Farms (see figure 5). The Wood River and Seven Mile River are the sources of water for Agency Lake. The remaining flow into Upper Klamath Lake is from numerous smaller point source springs and streams, which are spread around the lake.

A discharge hydrograph of the Williamson River for an example water year shows the seasonal pattern of river flow (figure 2). Mean-daily flows slowly rise during the beginning of the water year and remain somewhat high during the winter. Since much of the precipitation falls as snow at high elevations, the period of highest mean daily flow occurs during the spring snowmelt season, which typically occurs during March, April, and May. Flow continues to decline throughout the summer, typically reaching a minimum flow during August and September. Large floods tend to occur during winter from rain on snow events. Figure 2 shows that the period of highest mean daily flows corresponds well to the period of highest lake elevations (Figure 1). Mean daily flow statistics were available for the Williamson River from the USGS WEB site[1]. Figure 3 shows the maximum and minimum recorded mean daily flows, and the 25, 50, and 75 percent exceedance flow levels for each particular day of the year. Minimum mean daily flows in the Williamson River range from 300 to 600 ft^3/s. Maximum mean daily flows in the Williamson River occur in December and January and the maximum recorded mean daily flow is 17,100 ft^3/s, which occurred January 5, 1997. Figure 3 shows that flows are typically highest during the spring snowmelt season (March, April, and May), but also during winter floods that typically occur during December, January, and February.

[1] http://nwis.waterdata.usgs.gov/or/nwis/discharge/?site_no=11502500

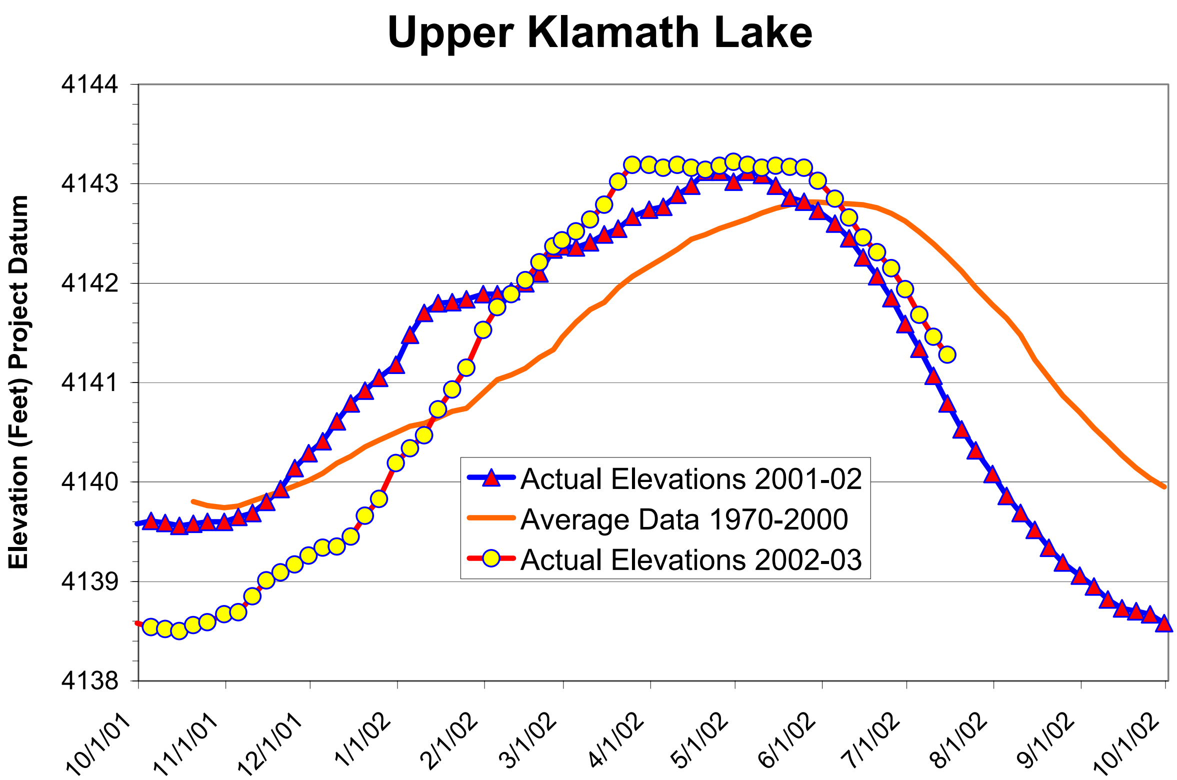

Figure 1. Upper Klamath Lake water surface elevations (feet, USBR datum) throughout the water year. Curves shown are the average water surface elevation for the period from 1970 to 2000, the 2002 water year, and part of the 2003 water year. Data is from the USBR Klamath Basin Area office.

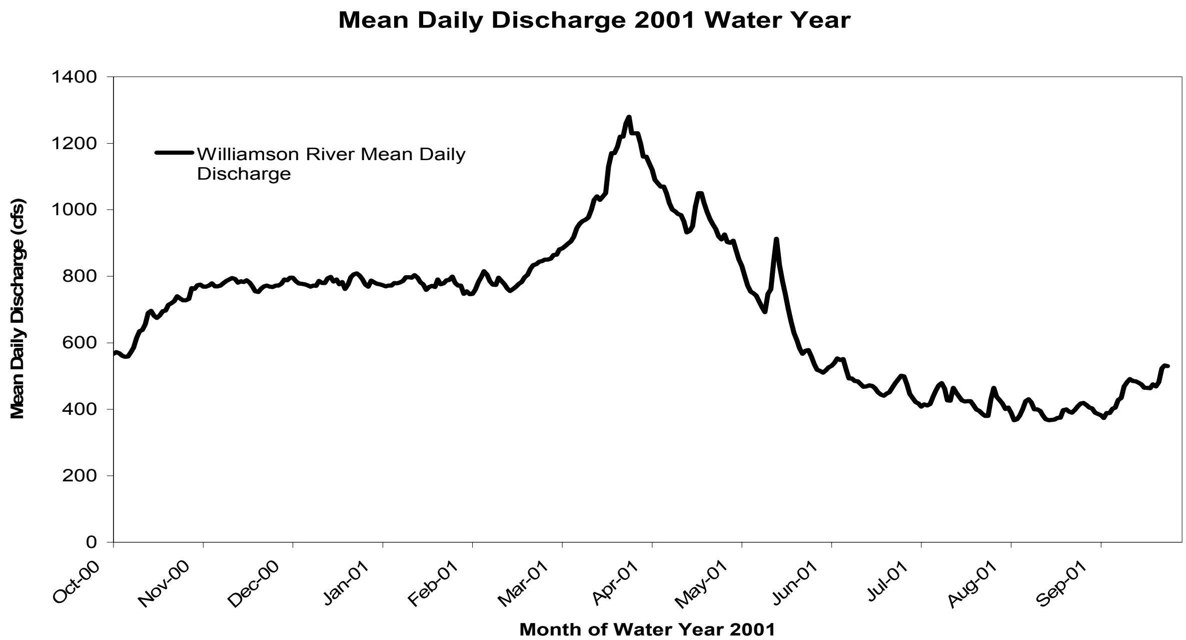

Figure 2. Mean-daily discharge hydrograph of the lower Williamson River for the water year 2001 (October 1, 2000 through September 30, 2001).

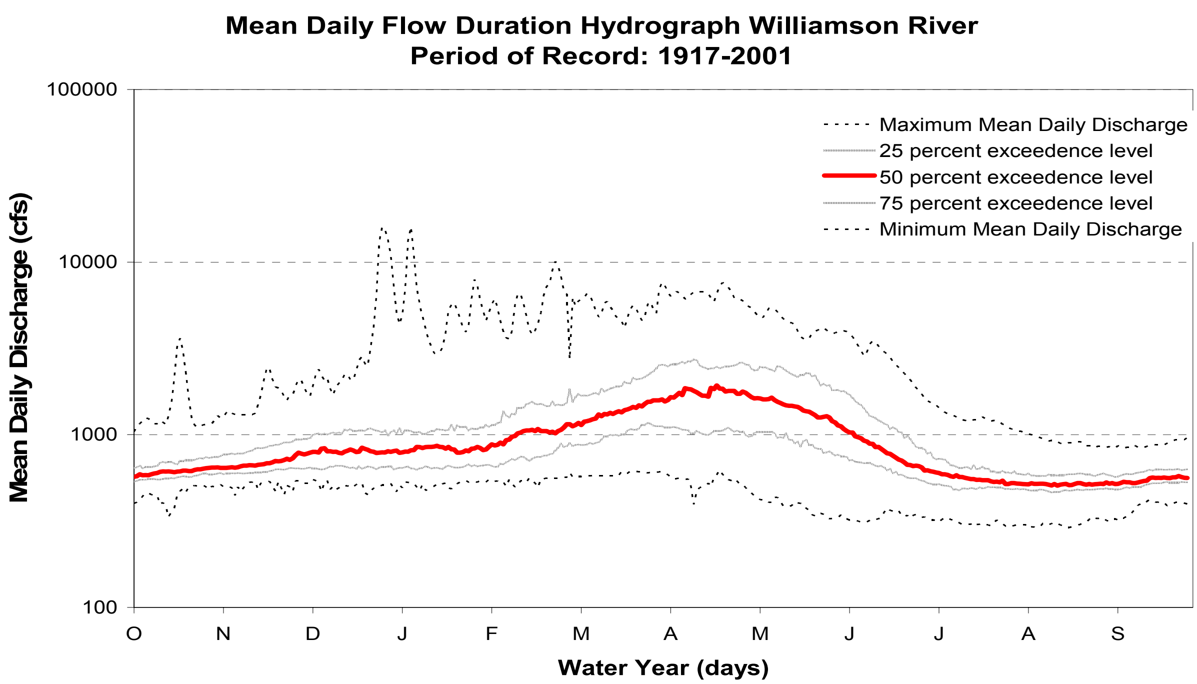

Figure 3. Mean daily flow duration hydrograph for the Williamson River. The lower line of the figure shows the minimum recorded mean daily discharge for each day of the water year. The next three lines shows the flow rate that is equaled or exceeded 75, 50, and 25 percent of the the time for each day of the water year. The top line is maximum-recorded mean daily discharge for each day of the water year.

Figure 4 is an approximate flood frequency curve that predicts the annual flood peak for a given return period. According to curve in figure 4, the annual flood peaks for is the 1.5-year flood is 2,070 ft^3/s, the 2-year flood is 3,020 ft^3/s, and the 100-year flood is approximately 14,000 ft^3/s. . The flood insurance study for Klamath County, Oregon (Federal Emergency Management Agency, 1984) reported that the 100-year flood peak was 13,800 ft^3/s, but that was prior to the flood of record of 17,100 ft^3/s, which occurred on January 5, 1997 (see appendix). The mean-daily discharge for this record flood peak was 16,000 ft^3/s. The mean-daily discharge of 16,000 ft^3/s was used in this study as a conservatively high estimate of the 100-year flood.

The 1.5 year flood is commonly associated with the bank-full discharge for natural river channels. However, deltas are created when coarse sediments, being transported by the upstream river channel, deposit in the slow velocities of a lake or reservoir. Therefore, deltas are normally inundated by high lake elevations and the concept of bank-full discharge across the delta does not apply. Despite the fact that the bank-full discharge is not directly applicable to this part of the Williamson River, the flow rate defined by the 1.5 year flood occurs frequently and is considered a representative flow for this study.

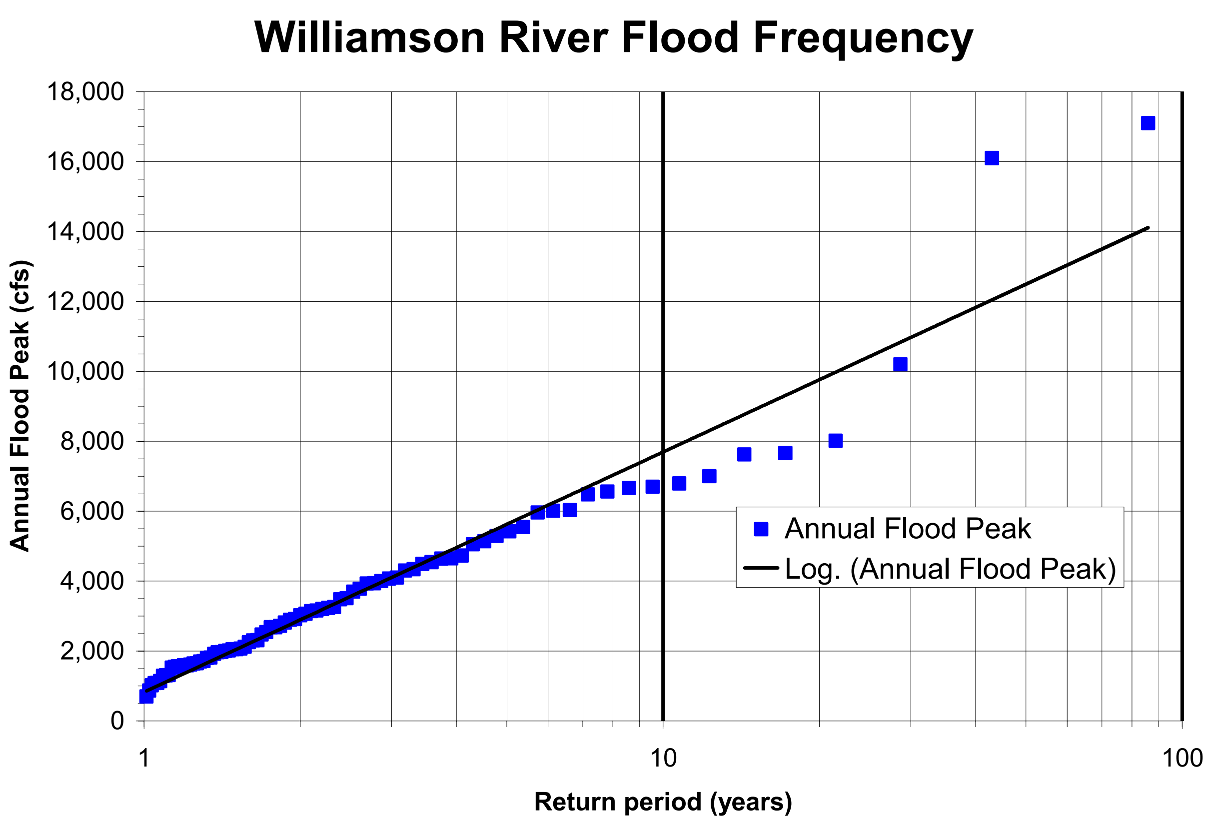

Figure 4. Approximate flood frequency curve for the Williamson River downstream from the confluence with the Sprague River.

Figure 5 is an aerial photograph from circa 1996 that shows the current conditions of the floodplain/delta and the existing alignment of the river. The remnants of the former channel alignment are evident by the presence of an oxbow channel in Goose Bay that has been cut off from the river channel by the left-side levee. Levees are present along both sides of the river beginning from the area of the Riverbend site at river mile 3.2 and extending to the mouth of the river. These river levees would contain the 100-year flood peak and prevent water from flowing onto the floodplain/delta from the river. Levees are also present along the entire length of lake shoreline (see figure 5). The lake shoreline levees keep water from Agency Lake in the north and Upper Klamath Lake in the south from entering the lake delta. In order to facilitate river navigation by boat, the river has been dredged in the past down to an elevation that is lower than the current lake bottom elevation adjacent to the river mouth. This dredging extends upstream through the entire property.

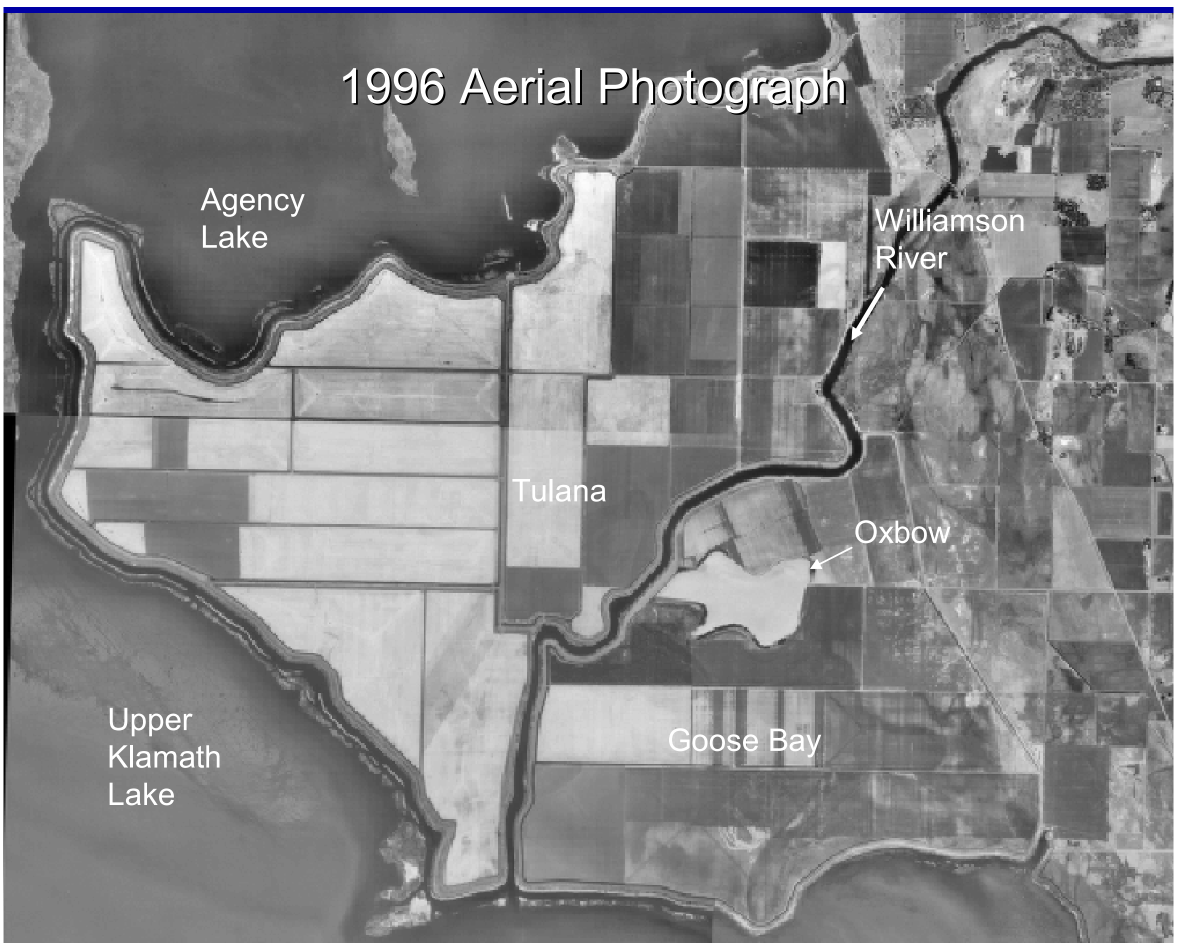

Figure 5. Recent aerial photograph (1996) of the Lower Williamson River system.

4.0 Methods

4.1 Study Approach

The following summarizes the basic approach taken in this study.

- Since all of the levees can't be breached due to financial and cultural resource limitations, the levees will only be breached at strategic locations.

- Use an objective approach, where the strategic breaching of levees is based on the locations where most of the flow would cross the levee boundaries in the absence of any levees.

- Compare the two-dimensional flow patterns of various modeled levee-breach scenarios to the two-dimensional flow patterns of the base conditions without any levees.

- Refine the location and length of strategic levee breaches to best match the two-dimensional flow patterns of the base condition.

- Use historic information to evaluate changes in channel alignment and geometry, identify potential opportunities for restoring channel form, and evaluate hydraulic benefits.

In order answer the questions put forth in section 1, both 1-Dimensional (1-D) and 2-Dimensional (2-D) numerical models were used.

4.2 Assessment of River Alignment and Channel Width

A comparison was made between the historic river channel alignment and the current alignment based on a recent aerial photograph (circa 1996) available from the USGS, an aerial photograph mosaic of the study area taken from 1940-1941, obtained from TNC, and a plat map from the late 1800's, dated from 1840-1890, also obtained from TNC. Changes to the channel alignment and width were compared over these three time periods. In addition, a previous analysis of channel widths was reviewed. The 1996 photograph was available in NAD 1983 State Plane Oregon South FIPS 3602. To be consistent with data already in use, the 1996 photograph was projected to the NAD 1927, UTM Zone 10N datum. The 1940-41 photograph mosaic and the historic plat map also had to be transformed to this same datum to allow visual comparison of existing conditions with the historic photograph and plat map.

TNC provided the 1940-41 historic aerial photograph mosaic as a digital image and the plat map was provided in the AutoCAD format. The following procedure was performed by Kurt Wille of the Bureau of Reclamation's Remote Sensing and Geographical Information Group to rectify the 1940-41 photographs with the 1996 photograph. The historic images were geo-referenced and rectified to the horizontal control points that were derived from the 1996 digital ortho photograph (DOQ) at a one-meter pixel resolution. The historic photograph scans were geo-referenced using

ESRI software. Control point values were transferred from an image point on the DOQ (example: road intersection, tree) to the same image point on the scanned photograph. A first-order transformation technique was utilized to rectify the scanned photos. The DOQs meet National Map Accuracy Standards (NMAS); however the resulting images may not meet NMAS.

4.3 Two-Dimensional (2-D) Model

Two-dimensional (2-D) models predict water depth and the depth-averaged flow velocity for each grid cell of the model area. This project utilized DHI's MIKE21, 2-D hydrodynamic flow model (DHI Water & Environment, 2002). MIKE21 is a 2-D finite difference model that simulates unsteady flows in vertically homogenous fluids using the Saint-Venant equations. The model was run until a steady-state solution was found for a constant flow rate that simulated 2-D flow patterns across Goose Bay, Tulana Bay, Upper Klamath Lake, and Agency Lake.

The 2-D model uses a digital elevation model (DEM) grid and computes the water depth and a velocity vector (magnitude and direction) for each wetted cell at every time step of the model simulation. A DEM of the delta, floodplain, and river channel bottom was provided by TNC. A separate DEM was provided by the Reclamation's Klamath Basin Area Office, which included the bathymetry of Upper Klamath Lake and Agency Lake. These DEM's were combined and a 10 meter resolution DEM was created that included the Williamson River, from just downstream of the Modoc Point bridge to the river mouth at Upper Klamath Lake, the floodplain and delta area, the southern portion of Agency Lake, and the northern portion of Upper Klamath Lake. The combined DEM data were in a 1927 North American Datum, UTM Zone 10 North projection.

The 10-meter DEM represents the bottom topography of the river channel, floodplain, delta, and lakes. The other input data that are required for the 2-D model include the bottom roughness, an estimate of eddy viscosity, the initial depth, and the upstream and downstream boundary conditions. The flow rates to the study area, and their locations, represent the upstream boundary conditions. The lake elevation represents the downstream boundary condition. Figure 6 shows the extent of the modeled area including the boundary conditions for the base condition (discussed below).

The upstream boundary conditions were modeled as constant flow boundaries in the river and in Agency Lake. The downstream boundary conditions are represented by a constant water surface elevation within Upper Klamath Lake where water flow exits the model area. The initial conditions are specified with an initial water surface elevation at all points within the grid that are inundated, including the lakes, river, and floodplain/delta. The initial water surface elevation was set equal to the constant lake water surface elevation at the downstream boundary for all simulations. The effects of wind and temperature gradients are not modeled because they were beyond the scope of this study. The location and type of boundary condition remained constant for all simulations performed. However, the steady flow rates representing the Williamson River and Agency Lake, and the water surface elevation of Upper Klamath Lake, varied among the model simulations.

The MIKE21 model only uses the SI system of units. Therefore, all results obtained from the MIKE21 model are reported in SI units (i.e., cubic meters per second (m^3/s) for flow rates, meters per second (m/s) for velocity, and meters (m) for water depth, elevations, and all horizontal distances).

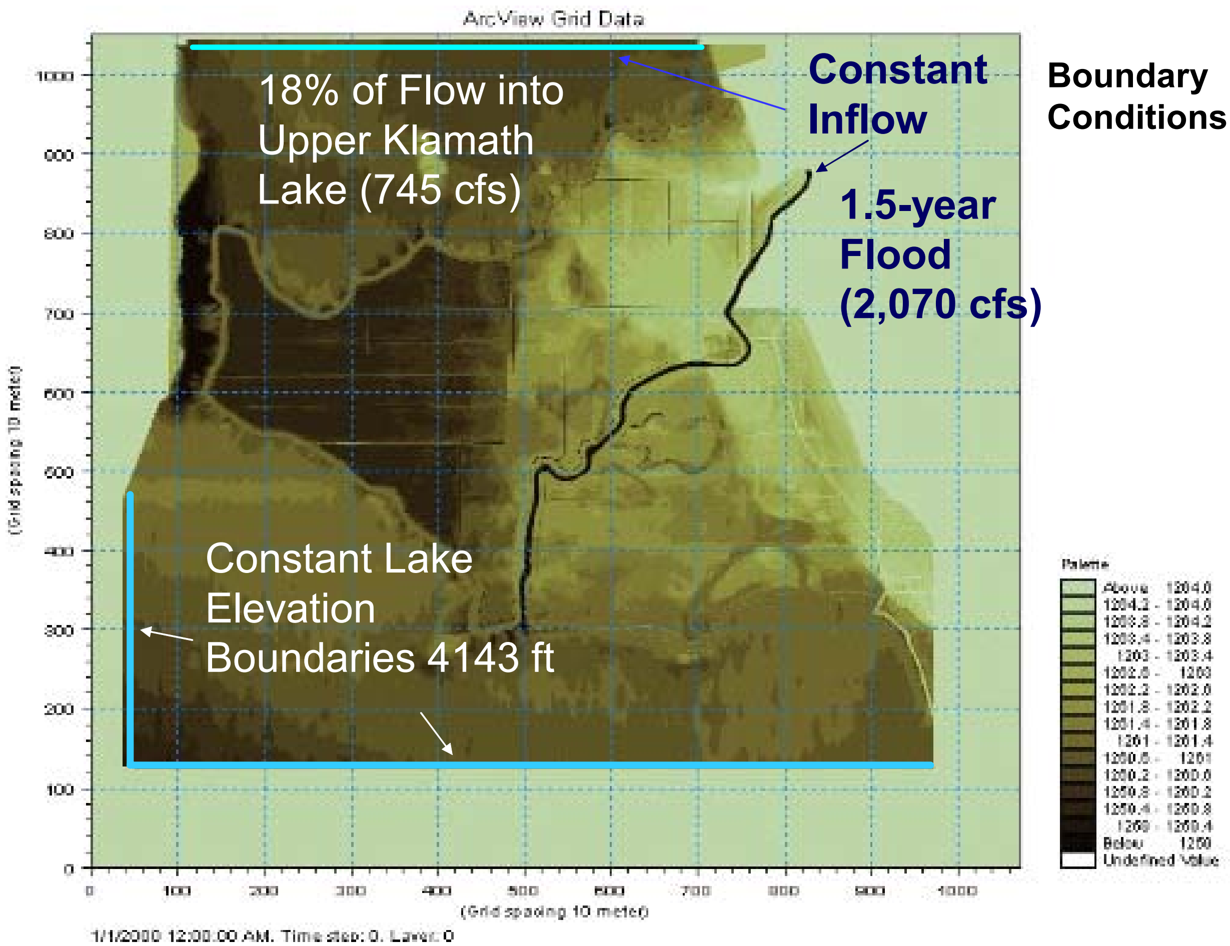

Figure 6. 10 meter grid representation of the study area. Lightly shaded areas (green) around the outside of the grid are outside the model boundaries and represent a "wall" that contains the water within the modeled area. Darker shaded areas (brown) are land surfaces of lower elevation (submerged beneath lake or river), and lighter colors are land surfaces of higher elevations. The locations of the upstream and downstream boundary conditions are as shown.

4.4 One Dimensional (1-D) Model

The US Army Corps of Engineers, Hydrologic Engineering Center, developed the River Analysis System (HEC-RAS) model (version 3.1) to simulate the 1-D hydraulics of a river channel. This model was used to compute the change in flood stage caused by levee breaches and channel modifications. In order to generate accurate cross sections of the river channel, a one foot contour map of the lower Williamson River delta floodplain, provided by TNC, was used to generate a triangulated integrated network (TIN) of the study area using ArcView GIS.

The US Army Corps of Engineers, GIS interfaced, HEC geo-RAS software, was used in ArcView 3.2a to generate cross sections of existing conditions from the TIN for import into HEC-RAS model. Cross sections created in this manner were found to correspond precisely with measured cross sections reported by Graham Matthews & Associates (2002). Graham Matthews & Associates (2001) utilized the HEC-RAS model in a study of the hydraulics of the Williamson River and calibrated the model roughness coefficients to match the measured water surface elevations. A constant Manning's *n* roughness coefficient of 0.026 was determined from the calibration and used in this study as well. A Manning's *n* roughness coefficient of 0.05 was used for overbank areas, which is also consistent with the study by Graham Matthews & Associates (2001). These same roughness values were used in the MIKE21 two-dimensional model.

The 10 meter grid representing the topography in the MIKE21 model was modified to represent several different levee breach scenarios. The modified grids were then used to create cross sections for HEC geo-RAS simulations that included levee breaches and alterations to the channel geometry. The levee and channel topography was modified using MIKE21 and converted from a grid file to an ASCII file for import into ArcGIS. This grid could then be imported into ArcMap or ArcView. In order to generate a TIN for use in ArcView and geo-RAS, ArcToolbox was used to convert the GIS grid to a TIN. The TIN file was imported into ArcView, cross sections were generated that included the river channel and the entire floodplain/delta (see figure 7). The cross section alignments were bent to conform to the delta topography. The HEC geo-RAS model was used to generate a geometry file for import into HEC-RAS.

The 1-D hydraulic model uses cross sections of the river and floodplain/delta topography to compute a level water surface elevation and average flow velocity across the section for a given river flow. Two model boundary conditions are needed in order to run the HEC-RAS model: an upstream boundary in the form of a flow rate and a downstream boundary in the form of a water surface elevation. Various upstream and downstream boundary conditions were specified for each model scenario (see section 4.4).

The 1-D model works very well to determine water surface elevations and average velocities across a user defined cross section. This serves the purpose of determining at what flow rates and locations flow may get out of bank in the absence of levees, and it determines the effects on upstream flood stage as a result of downstream modifications. However, a 2-D model is required to simulate the more complex depth and velocity patterns of flow across the floodplains, deltas, bays, and lakes.

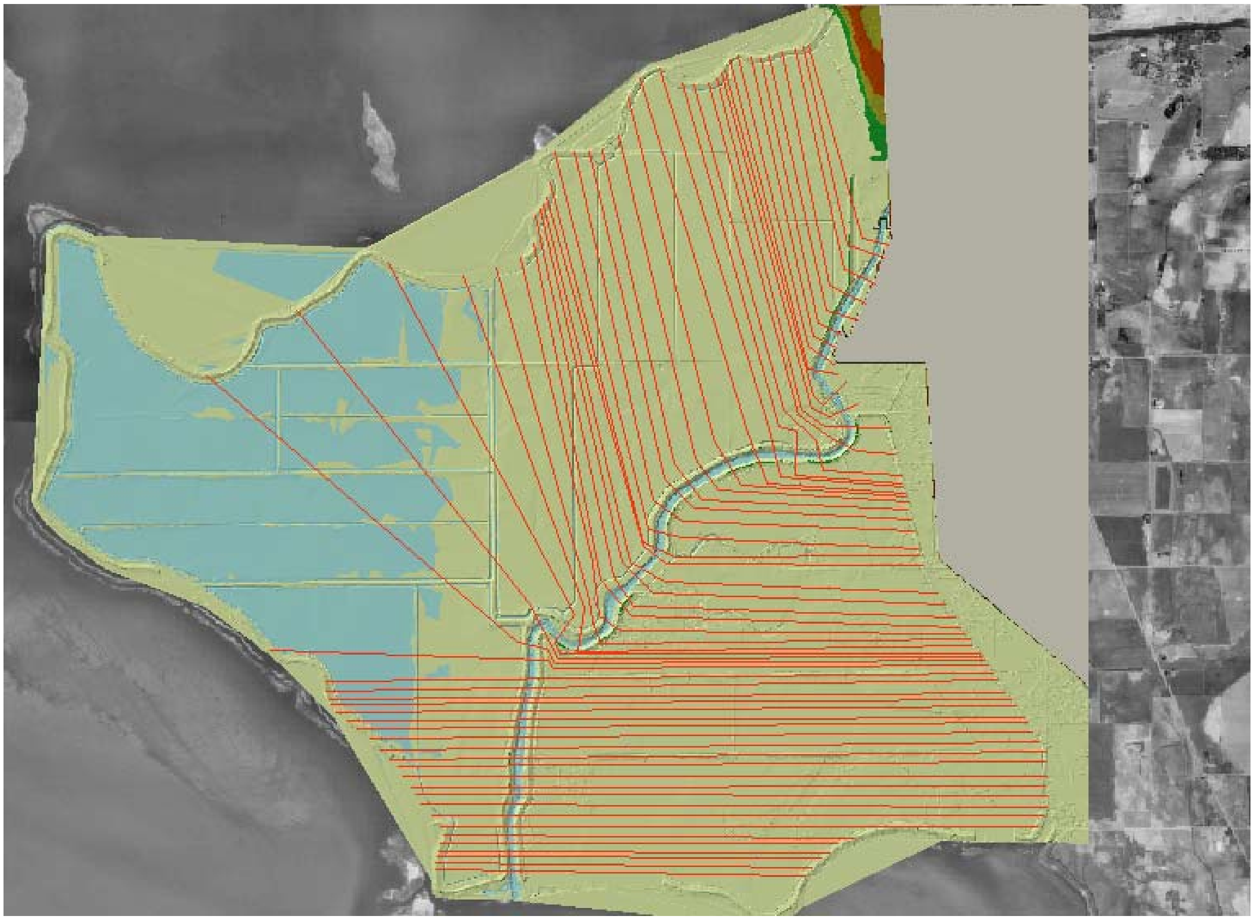

Figure 7. Cross sections used in HEC-RAS (red) were overlaid on the TIN representing the topography for a given 2-dimensional model scenario. The TIN in this figure is overlaid onto the 1996 aerial photograph.

4.5 Base Condition

A simulation was performed where all river levees and shoreline levees were not present. Levees were removed using the grid editor in MIKE21. River levees were removed to the elevation of the adjacent floodplain; therefore not all sections of river levee are removed to the same elevation. Shoreline levees were removed to an elevation of 4138 feet. Figure 8 shows the grid representing the existing topography (bathymetry) of the study used in MIKE21. The colors in figure 8 represent the elevation of the land with darker colors representing higher elevation surfaces (opposite the scaling in figure 7). The levees that surround the delta and river are apparent in figure 8. Figure 9 shows the same grid with the levees removed by lowering the elevation of the existing levees as described above.

The purpose of complete removal of all levees is to determine where river flow will enter the floodplain in the absence of levees. For instance, if an area of the floodplain adjacent to the river shows flow in a direction that is generally parallel with the river channel, then this area would not be a prime area where flow gets out of bank. Therefore, an area such as this is less valuable as a location to breach levees. However, in the absence of levees, if an area of floodplain adjacent to the river shows a flow field that is generally perpendicular to the river flow, then this would be a potentially good location to breach the levee. The parameters of the base condition are as follows.

- Steady flow of the Williamson River is 2,070 ft^3/s. This is representative of a 1.5 year flood event. This value provides an upstream boundary condition in the MIKE21 and HEC-RAS models.
- Net flow from Agency Lake into Upper Klamath Lake is 745 ft^3/s, which represents the second upstream boundary condition. The net flow from Agency Lake is 18% of the total flow into Upper Klamath Lake. Flow from the Williamson River is 50% of the total flow into Upper Klamath Lake. The remainder of flow into Upper Klamath Lake is from other sources not considered in this model.
- Lake water surface elevation is 4143 feet. This value provides the downstream boundary condition in the MIKE21 and HEC-RAS models.
- A 10 m DEM resolution was used with the MIKE21 model.
- Time step of the MIKE21 base simulation is 5 seconds.

In order to determine the location and quantity of flow out of the river and onto the floodplain, and the amount and location of flow from the floodplain into Upper Klamath Lake, the river and shoreline were divided into sections. Flow within the banks of the river was determined using tools in MIKE21 (MIKE21 toolbox, Hydrodynamics/discharge calculation tool) at 9 cross sections from the mouth of the river to the upstream most extent of overbank flow (figure 10). These cross sections were located at roughly equal distances along the river channel, but also at the beginning and end of meander curves. The flow within the banks of the river is measured at each cross section to determine how much overbank flow occurred between any two sections. Discharge across the digitally removed levees is measured on each side of the river to determine how much flow gets overbank between the cross sections on both the Tulana and Goose Bay sides of the river. Flow across each segment of interior levee and shoreline levee is determined in order to establish where the dominant flow path is across the floodplain and into Upper Klamath Lake. Shoreline levee sections for both Tulana and Goose Bay are shown in figure 10. Interior levee sections were numbered in a similar fashion.

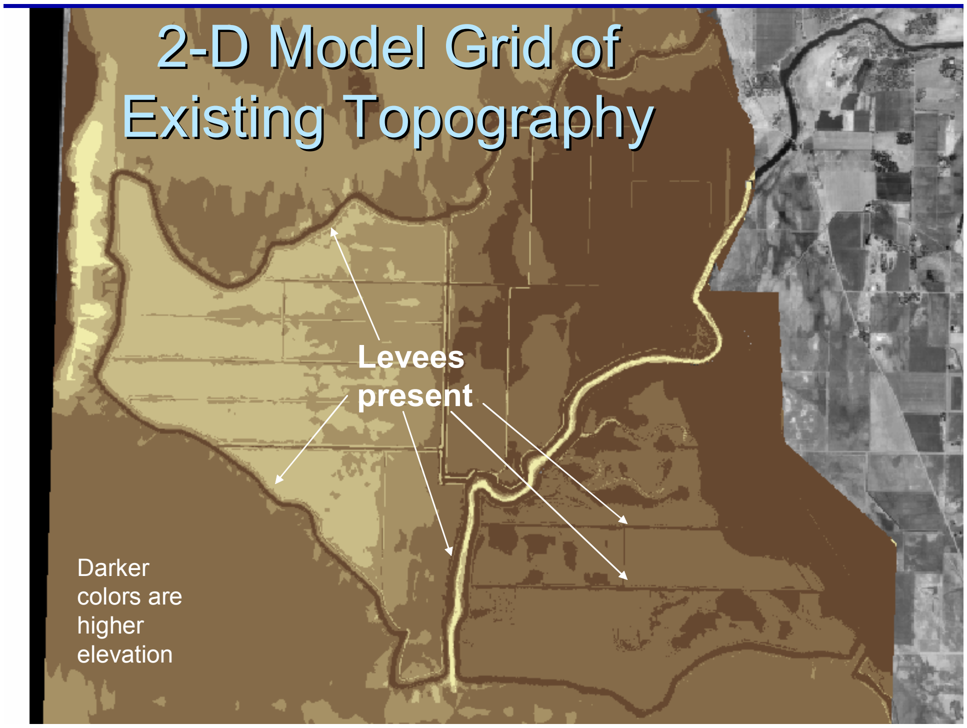

Figure 8. Existing topographic surface elevations of the study area with levees as represented in MIKE21. Lighter colors are lower elevations and darker colors are higher elevations.

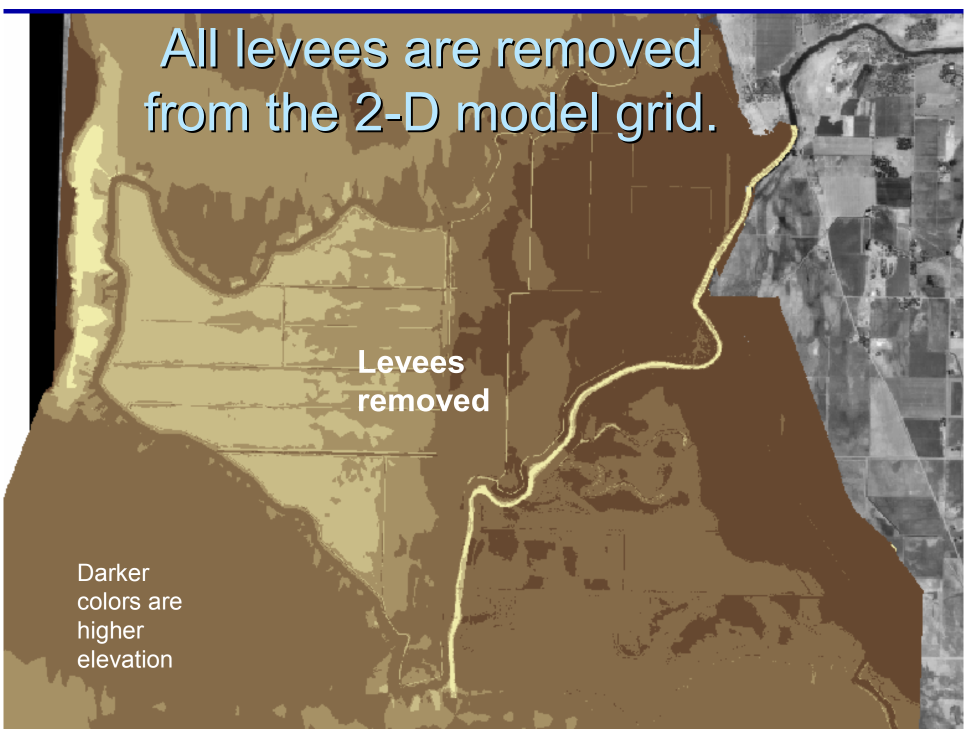

Figure 9. Topographic surface elevations of the study area with levees removed as represented in MIKE21. Lighter colors are lower elevations and darker colors are higher elevations.

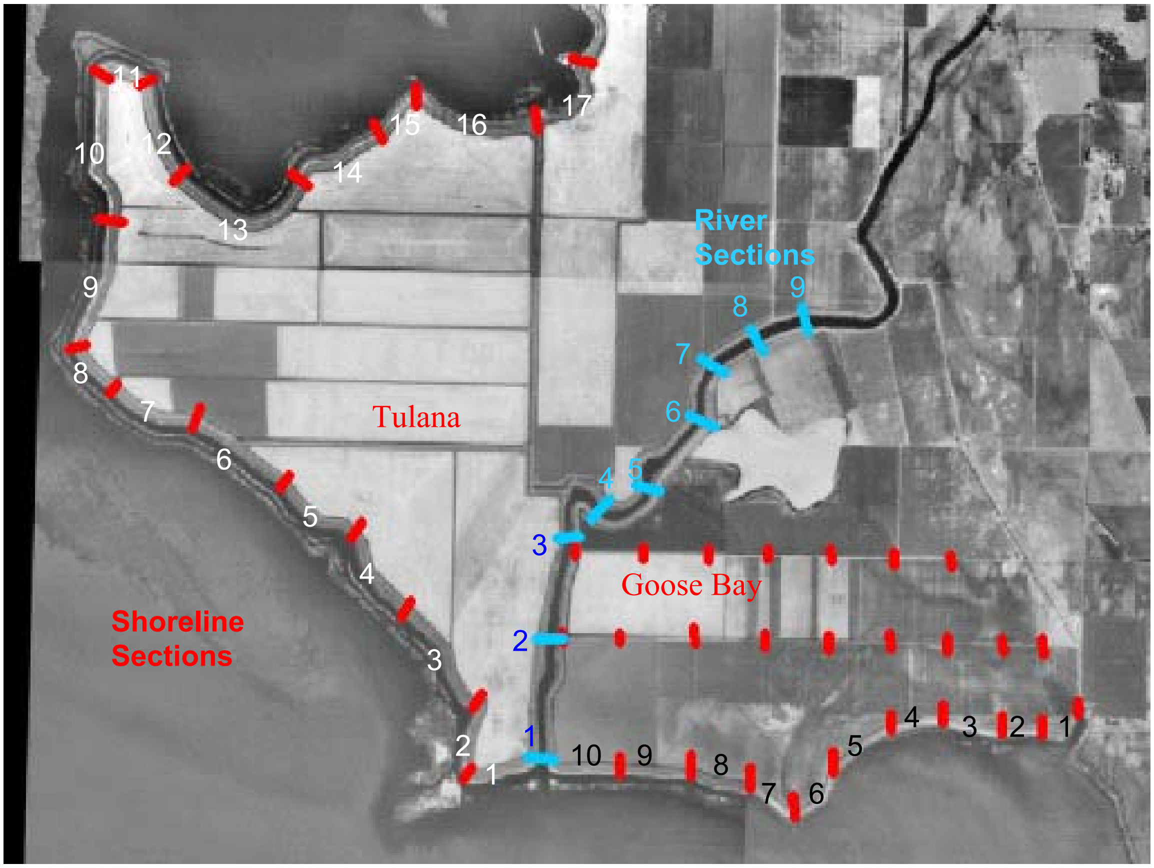

Figure 10. Sections used to quantify flow passing over digitally removed river levees (between blue sections) and the flow passing over the digitally removed shoreline and interior levees (between red sections).

The time step for all model scenarios was determined in the following manner. The model was run at the largest time step possible (according to the Courant number), and then re-run with the time step reduced by at least one half to test if the model results were still essentially the same. If not, the time step was again reduced by at least one half and the model was run again. For example, a time step of 5 seconds was run for the base condition and a time step of 2 seconds was then run. The results of each simulation were compared by using a difference grid of the water depths for each simulation. If there was no significant difference in the water depths, the larger time step was used so that the model could be run more quickly. Difference grids showed water depth differences less than a tolerance of 1 mm between the 5 second and 2 second time steps. The small difference in water depths of 1 mm provided confidence that the 5 second time step was a reasonable choice for the model simulations.

4.6 Key Model Scenarios

Information from the base condition was used as a guideline for identifying the location of potential levee breaches. Various model scenarios were performed to evaluate the effects of different combinations of levee breaching and channel modifications. Key model scenarios include:

- Breaching river and shoreline levee segments at selected locations to allow flow through Goose Bay.

- Breaching river and shoreline levee segments to allow flow through Tulana as well as Goose Bay.
  - Breaching shoreline levee segments along the shorelines of Agency Lake and Upper Klamath Lake
  - Breaching shoreline levee segments only along the shoreline of Upper Klamath Lake

- Re-establishing the oxbow channel

- Re-establishing the oxbow channel and fill in the existing river channel segment between the oxbow loop

- Re-establishing a historic delta channel at the river mouth

Table 1 shows a summary of the parameters used in each of the key scenarios, including upstream and downstream boundary conditions, time step, location of levee breaches, and channel modifications. Details of the conditions for each simulation and results are given in section 5. A discussion of the results of the base condition is followed by a discussion of setup and results of additional simulations in section 5.

4.7 Volume of Levee Material Moved

The volume of levee material removed was estimated using two methods:

1. The levee breach dimensions were calculated using GIS, including the breach length, average bottom and top width of the levee, and the average levee height. The levee breach volumes were then computed by multiplication of the breach length, average width, and average height.

2. As a check on the first method, the levee breach volumes were also computed by taking the difference between the DEM terrain surface of existing conditions (with the levees in place), and the DEM terrain surface with the levee sections removed. A new 1 m DEM terrain surface of the existing conditions was created from topographic data to improve the accuracy of the calculations. The MIKE21 grid editor was used to select the set of grid cells that represent each levee breach area. The elevations of these areas were set equal to the elevations of the surrounding delta/floodplain. In ArcMap, the 10 m DEM with levees removed was re-sampled to produce a 1 m DEM. Using the raster calculator, a difference grid is generated by subtracting the modified bathymetry grid from the elevation grid for existing conditions. This difference grid gives the elevation differences between each elevation grid, and thus provides the depth of levee removal (in meters). The depth of material removed was multiplied by the area of each grid (100 m^2) to obtain

a volume estimate in cubic meters, which was converted to cubic yards. A volume estimate was done for each simulated river, interior, and shoreline levee breach.

The volume of material moved from the oxbow to re-excavate the channel is estimated in the same manner. The volume estimate for channel narrowing is an estimate of the amount of material required to fill the channel to the new elevations.

Table 1. Upstream Boundary (Williamson River discharge and Agency Lake discharge, ft^3/s), downstream Boundary (lake water surface elevation, ft), MIKE21 time step (seconds), location of levee breaches, and channel alterations for each of the key model scenarios.

SCENARIO	Upstream Boundary Williamson River Discharge (ft^3/s)	Upstream Boundary Discharge from Agency Lake (ft^3/s)	Dowstream Boundary Lake Water Surface Elevation (ft)	MIKE 21 Model Time Step (sec)	Levee Breach Locations And Channel Alterations
Reference	2,070	745	4143	2	River levees removed at two sections on Goose Bay and one section on Tulana. Goose Bay and Tulana interior levee breaches are shown in figures 19 and 20. Shoreline levee breaches are located near river mouth on west and a smaller shoreline breach on the east in Goose Bay. Shoreline levee breaches are located at two sections along Upper Klamath Lake and two sections along Agency Lake in Tulana. There are no channel alterations.
River Mouth Restoration	2,070	745	4143	2	The river, interior, and shoreline levee breaches are the same as in the Reference Scenario. In addition, river levee breaches are included on both sides of the river near the river mouth. Excavation of a historic delta channel is included from the river mouth levee breach on the Tulana side extending to the southwest to Upper Klamath Lake.
Reference Scenario without connection to Agency Lake	2,070	745	4143	2	The river, interior, and shoreline levee breaches are the same as in the Reference Scenario, except there are no shoreline levee breaches along Agency Lake.
Oxbow Channel Restoration					
Scenario 1	2,070	745	4143	2	The river, interior, and shoreline levee breaches are the same as in the River Mouth Restoration Scenario, including the excavation of the historic channel at the river mouth. In addition, the entire Oxbow channel is re-excavated to elevation 4136 feet and the main channel is filled in between the entrance and exit to the oxbow channel to the elevation of the adjacent floodplain.
Scenario 2	2,070	745	4143	2	The river, interior, and shoreline levees breaches are the same as in the Reference Scenario. In addition, the entire Oxbow channel is re-excavated to elevation 4136 feet and the main channel cutoff is left open.
Narrowed Channel	2,070	745	4143	2	The river, interior, and shoreline levee breaches are the same as in the Reference Scenario. In addition, the river channel is narrowed from the downstream most river levee breach (downstream of oxbow) to the river mouth by 1/4 to 1/3.
100-year Flood; Low Lake Elevation	16,000	1,415	4140	1	The river, interior, and shoreline levee breaches are the same as in the Reference Scenario, but the 100-year flood is simulated.
Average June Hydrologic Conditions	850	152	4142.1	2	The river, interior, and shoreline levee breaches are the same as in the Reference Scenario, but a low flow and low lake elevation are simulated.

5.0 Results

5.1 River Alignment and Channel Width

Figure 11 is an aerial photograph mosaic of the study area taken from 1940-1941 obtained from TNC. The light blue lines on the photograph outline the alignment of the river and shoreline in the 1940-41 photographs. The red lines superimposed on the photograph represent an approximate alignment of the river from a plat map recorded in the late 1800's (1840-1890). Figure 11 shows that the alignment of the river moving downstream from the northern extent of the photograph to the southward bend in the oxbow is essentially unchanged over the time period of the two maps. From this point, the alignment of the river appears to be somewhat different from the time of the plat map to 1940-41. The general direction and location of the river has not changed significantly in this reach. The difference in the location of the river channel between the plat map and the 1940-41 aerial photographs is about the same as the difference in lake shorelines and much of the lake shoreline should not have actually changed. Therefore, the differences in the location of the river channel may be due to inaccuracies of the plat map.

Figure 12 is a more recent aerial photograph of the area, circa 1996, with the alignment of the river channel from the 1940-41 photographs superimposed upon it. Figure 12 shows that the existing alignment is very similar to the alignment observed in the 1940-41 aerial photographs with the exception of the present cutoff of the oxbow by levees, and at the river mouth.

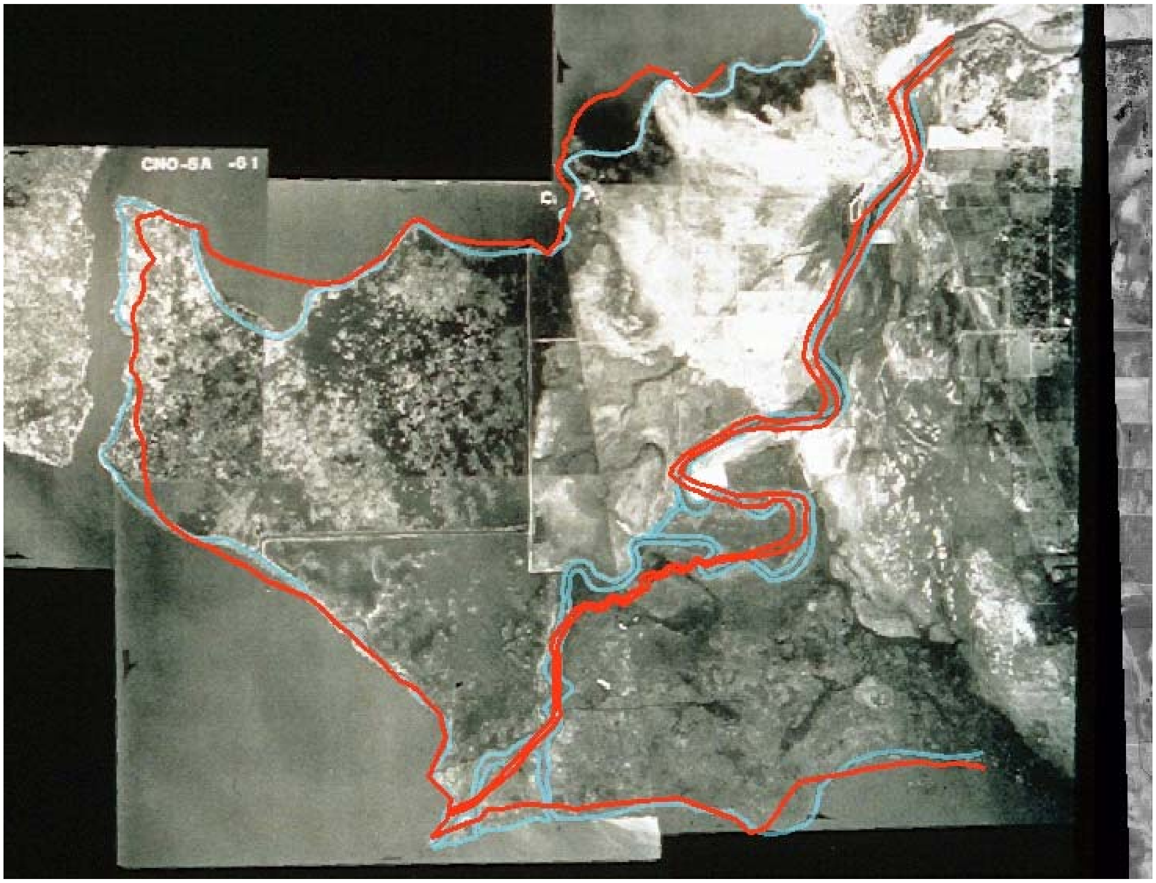

Figure 11. Plat map of river alignment and shoreline from around 1840-1890 (red) superimposed upon a 1940-41 aerial photograph mosaic. Light blue lines highlight the alignment of the river and shoreline in the photograph.

Figure 12. River alignment and shoreline (blue) from 1940-41 aerial photographs superimposed onto the 1996 aerial photograph.

Figure 13 shows a zoomed in view of the oxbow area with the 1940-41 alignment superimposed on the 1996 photo. It is clear that the old oxbow, now cut off from the main channel by levees, matches the 1940-41 alignment fairly well. Presently, the oxbow channel is filled in with sediment and is much narrower and shallower than it was in 1940-41. This area would need to be excavated (i.e., made deeper and wider) in order to restore the channel to conditions found in 1940-41. It is interesting to note that an initial cutoff channel of the oxbow can already be seen in the 1940-41 aerial photographs. It is not known if this was natural or if the cutoff channel had been mechanically excavated.

Figure 13. Oxbow reach of the study area showing the 1940-41 alignment (blue) over the 1996 aerial photograph.

Figure 14 shows a zoomed in view of the river mouth where the Williamson River flows into Upper Klamath Lake. The 1940-41 photographs shows 3 distributary channels at the river mouth, which flow into Upper Klamath Lake. There is some question as to whether or not the distributary flowing directly south into Upper Klamath Lake is natural or if it is a human-made channel. However, it is common for distributary channels to be straight, and unless there is documentation of the creation of this channel, there is no evidence that it is not natural. River and shoreline levees have been constructed at the river mouth since the 1940's and have locked the river mouth into a fixed position, cutting off the southwestern flowing distributaries. The levees have eliminated the possibility of further distributary delta channel formation. Restoring the historic oxbow and distributary channels at the mouth would restore a significant portion of the historic river channel alignment and connection of the river with the floodplain/delta.

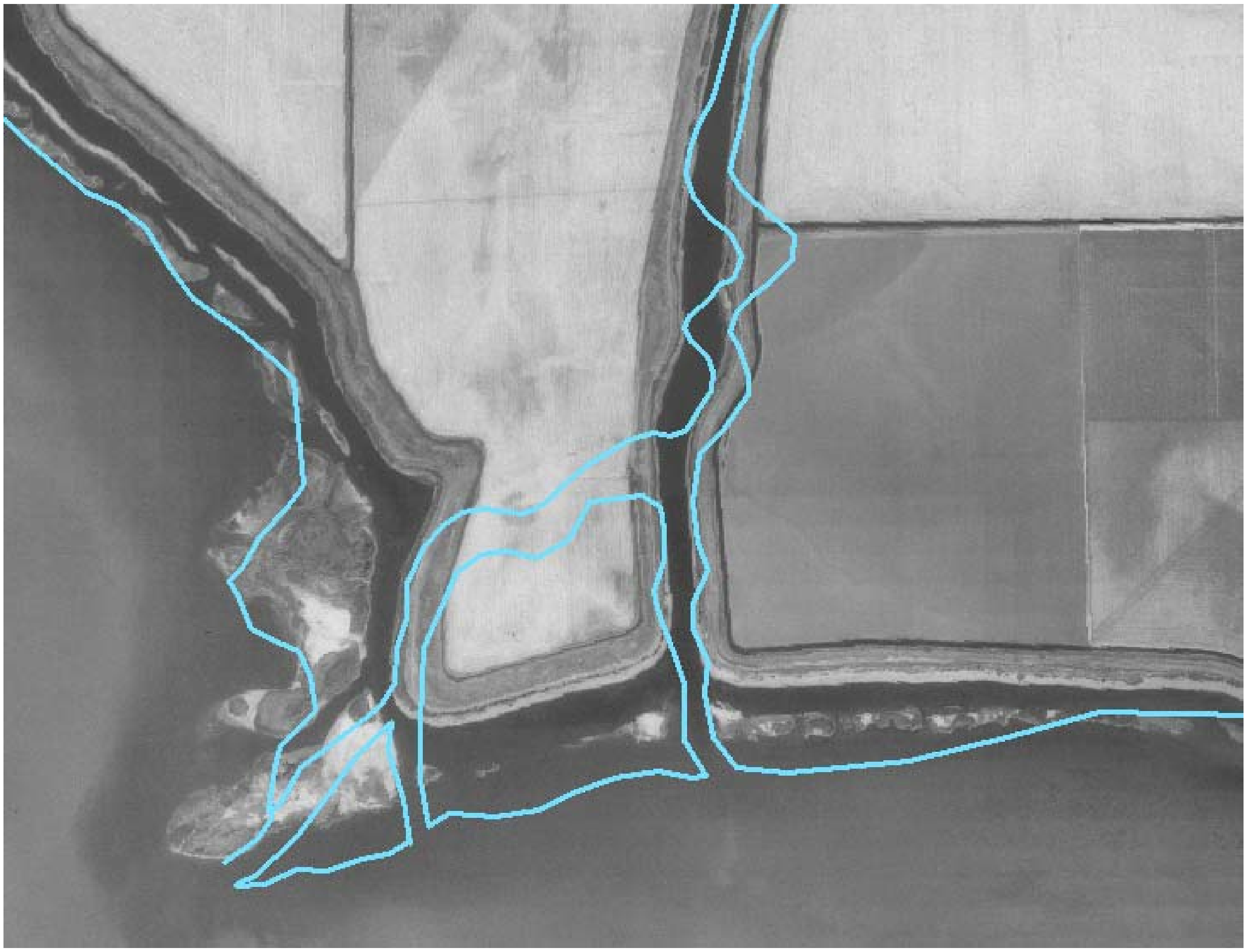

Figure 14. River mouth reach of the study area with the 1940-41 alignment (blue) over the 1996 aerial photograph.

It appears from the aerial photographs that the channel width in 1940-41 is of similar magnitude to the existing channel width. Graham Matthews and associates (1999) measured and compared the channel widths from the 1940-41 aerial photographs (same as the photograph used here) and the 1996 photograph to determine if any changes in width had occurred. Graham Matthews and associates (1999) found that the channel in the 1996 photograph is an average of 21 feet wider than the channel in the 1940-1941 photograph, in the reach upstream of the first westward bend of the river at the oxbow, and that the channel is an average of 65 feet wider in the 1996 photograph in the reach downstream of the last southward bend of the oxbow.

However, it is difficult to draw definitive conclusions from the data for two reasons. First, the range of recorded width changes along the river varies widely. In the upper reach, the channel width changes range from being 50 feet narrower at present than in 1940-41 to 113 feet wider at present than in 1940-41 (see table 2). In the lower reach, the range is from 82 feet narrower at present than in 1940-41 to 287 feet wider at present. It is not clear that the river is significantly wider throughout the entire study area given the range of values shown in table 2, and given that the standard deviation of the width changes is greater than the mean change for both reaches.

Second, the 1940-41 aerial photographs were likely taken from a high altitude and lack the clarity to measure distances with precisions less than 50 feet with any degree of confidence. There doesn't appear to be any obvious change in average channel width between 1940-41 and 1996. Since the standard deviation of width changes, measured from the aerial photographs by Graham Matthews and Associates (1996), is greater than the average width changes, the conclusion that the channel is now wider may be true, but it may simply be a product of the data errors in the analysis. Without some historical documentation that the channel was widened for a specific reason, or as a result of a specific action, it may be premature to conclude that the river channel is now significantly wider than in 1940-41. What is certain is that the existing remnant of the oxbow channel is significantly narrower than when the oxbow was active.

The relevance of the channel width pertains to the possible increase in conveyance of the river and its effect on the likelihood that water will get out of bank and flow onto the floodplain/delta with some frequency. The hydraulic analysis performed for this study shows that flow will get out of bank and onto the floodplain/delta with regularity so that channel alterations are not necessary to accomplish this goal. Furthermore, the river channel has been extensively dredged and deepened; the resulting increase in conveyance from this activity is likely much greater than any widening that may have taken place.

Table 2. Width changes in the lower Williamson River from 1940-41 to 1996 aerial photographs reported by Graham Matthews and Associates (1999). Positive number represents a wider channel in 1996 and a negative number represents a narrower channel.

	Width Change (ft)	
	Upper reach	Lower reach
	2	-82
	41	106
	-10	60
	37	287
	-50	137
	-34	127
	1	81
	-6	46
	63	115
	38	-30
	113	-34
	80	47
	-24	-24
	21	35
	44	59
	27	121
	61	138
	3	117
	-5	24
	-7	33
	34	-5
	20	
	54	
	-19	
	8	
	-1	
	44	
	-24	
	95	
Min	**-50**	**-82**
Max	**113**	**287**
Ave	**21**	**65**
Stdev	**39**	**81**

5.2 Results of Base Condition

The model set up for the base condition is discussed in section 4.4. The base condition is a representation of the Williamson River floodplain/delta system with all levees removed. This was done in order to determine flow patterns in the system in the absence of levees. Figure 15 shows a plot of the overall results of flow patterns in the study area under the base condition. The vectors represent the magnitude (m/s) and direction of the velocity of flow, and the background color represents the water depth (lighter blue is shallower water) over the floodplain/delta. Note: the largest velocity vectors of the 100-year flood are plotted with a wider arrow width. The plot has a reference vector plotted on the right side of the plot so that the magnitude of each vector can be estimated. Additionally, a legend showing the water depth color ranges is also located on the right side of each plot. Table 3 shows the amount of flow remaining within the river channel at each river cross section (see figure 10) and the amount of overbank flow on both sides of the river between each cross section. Figure 16 shows the amount of flow as a percentage of the total river flow (2,070 ft^3/s) that flows overbank to each side of the river. From table 3 and figure 16, it can be determined at what locations along the river the majority of flow goes onto the floodplain/delta on either Tulana or Goose Bay and where strategic levee breaches would be most effective. It is interesting to note that there is a return flow from Goose Bay back across the river near the mouth. This can be seen in figure 15 and in the graph in figure 16.

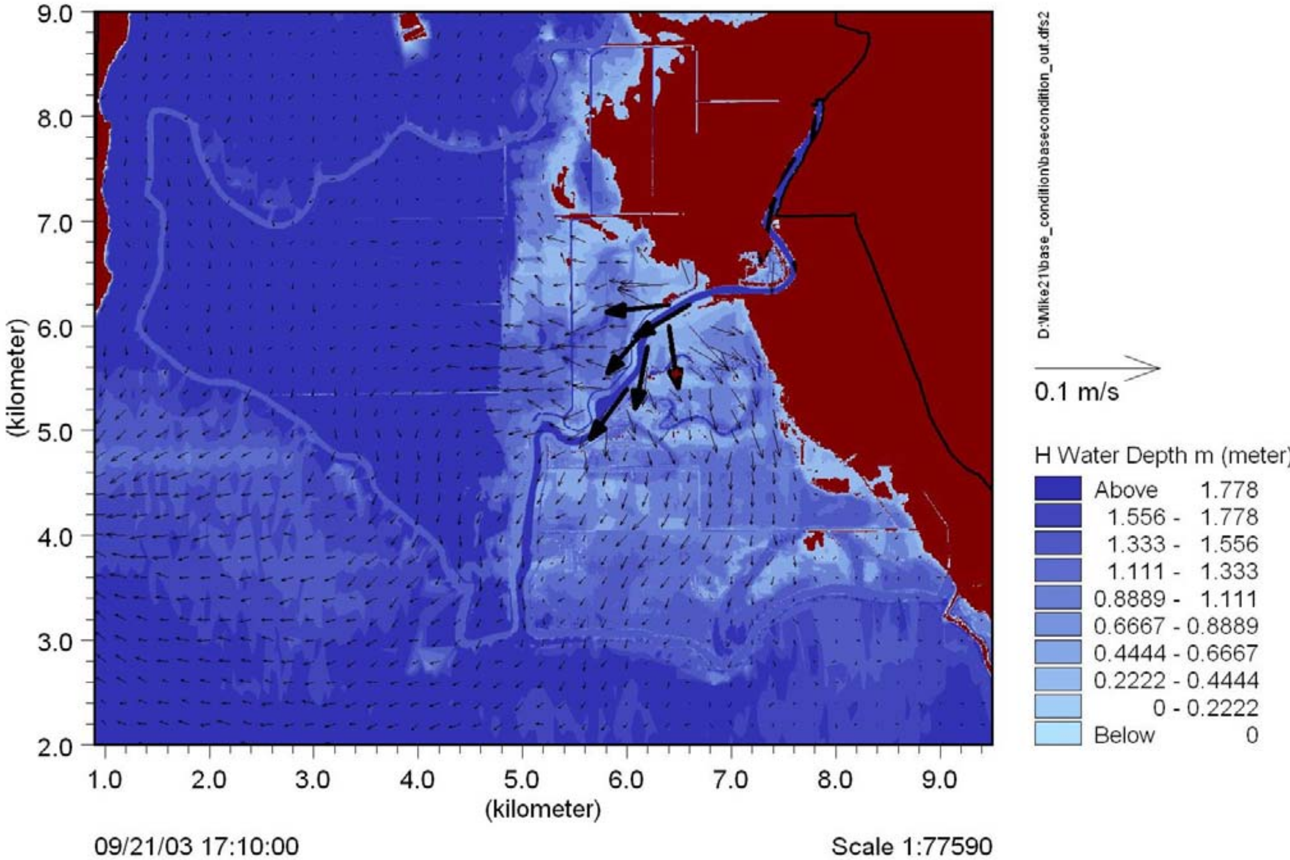

Figure 15. Velocity vector plot showing magnitude (m/s) of the velocity of flow and direction of flow through the study area for the base condition simulation. Water depth is represented by the background color, dark blue is deeper water than light blue.

Table 3. Quantity of flow (ft^3/s) within the existing river banks at the top of each river section, quantity of flow (ft^3/s) over areas where river levees have been digitally removed on both right and left banks of the river, and the percentage of total river flow that gets overbank on each side of the river within each river section.

Cross section	In Bank River Flow (ft^3/s)	Overbank flow (ft^3/s) between sections	Percentage of total flow (2,070 ft^3/s) getting overbank
River section 9	2,070		
River section 8	1,834	236	11.4%
River section 7	1,298	536	25.9%
River section 6	1,062	236	11.4%
River section 5	488	574	27.7%
River section 4	297	191	9.2%
River section 3	158	139	6.7%
River section 2	129	29	1.4%
River section 1	112	17	0.8%

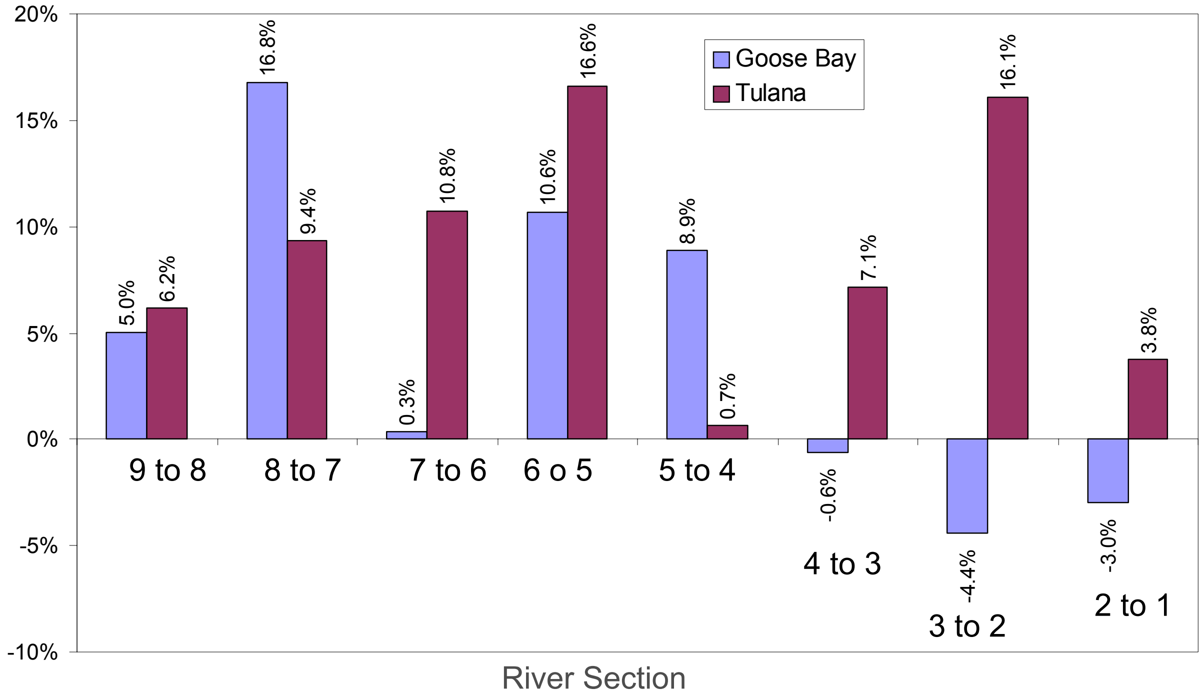

Figure 16. Percentage of total river flow getting out of bank on each side of the river between each river section.

The optimal locations for levee breaches on the Goose Bay side of the river are in the areas between sections 8 and 7, sections 6 and 5, and sections 5 and 4. The location between 8 and 7 will allow flow to get onto an area of the property that is more like a true floodplain since this area will only be submerged at the highest lake levels. This has significance with regard to the species of vegetation that may become established in this area, and breaches at this location may help to increase species diversity and richness in the study area. The location between sections 6 and 5 is in the area of the old oxbow and would serve to establish a reconnection of the oxbow with the main channel, and would restore much of the 1940-41 alignment. The area between section 5 and 4 is not as good a place to breach the levee since the river flow getting out of bank in that area will tend to flow back towards the river instead of onto the floodplain/delta.

The optimal locations for breaching levees on the Tulana side of the river are between sections 6 and 5 and between sections 3 and 2 in the lower part of the river near the mouth.

In order for water to flow freely over the floodplain/delta and into Upper Klamath Lake—in a pattern similar to what was observed in figure 15—levees in the interior of Goose Bay and Tulana along with shoreline levees must also be breached. Flow across interior and shoreline levee areas for the base condition (i.e., with levees removed) was measured in the same manner that flow from the river onto the floodplain/delta was measured. Figure 10 shows the location and number of shoreline sections where flow was measured. Figure 17 shows the percentage of total flow—through Goose Bay (672 ft^3/s)—through each shoreline section into Upper Klamath

Lake. It is apparent from figure 17 that the majority of the water flows into Upper Klamath Lake closer to the river mouth between sections 8 through 10. This pattern of flow can also be observed from the velocity vectors shown in figure 15 where flow is observed towards the southwest from about midway through Goose Bay into Upper Klamath Lake.

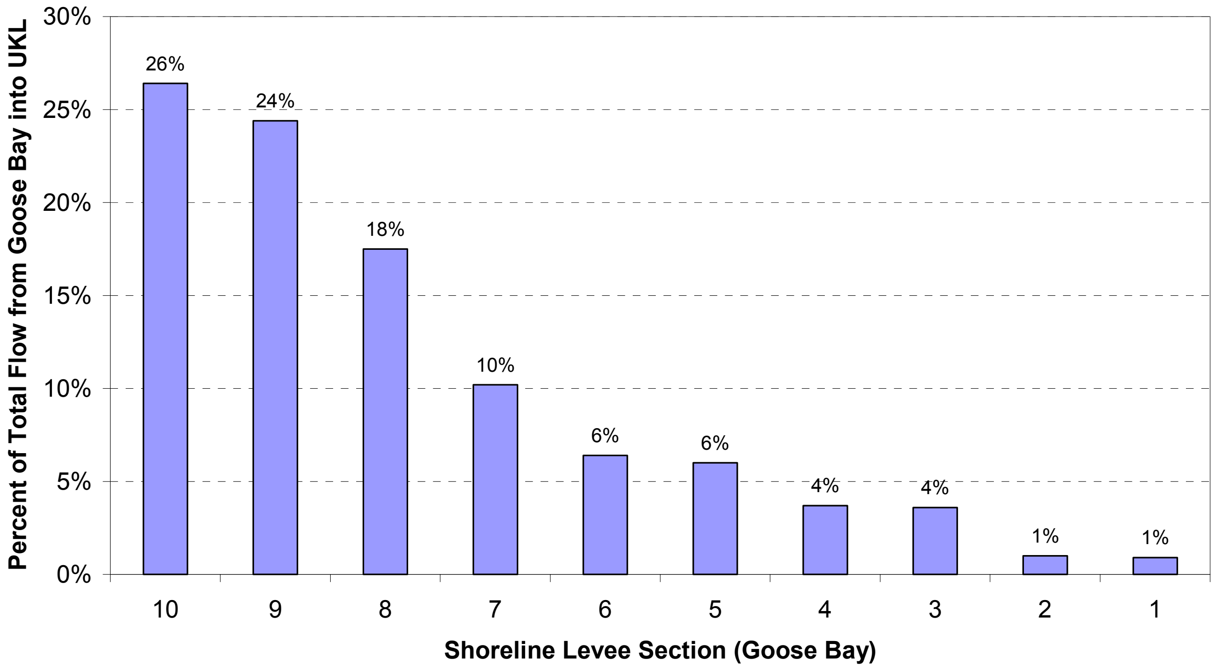

Figure 17. Percentage of total flow through Goose Bay (672 ft^3/s) that flows through each shoreline section between Goose Bay and Upper Klamath Lake.

Figure 18 shows the percentage (+) of flow (1,820 ft^3/s) crossing the shoreline into Upper Klamath Lake from Tulana and the percentage (-) flow (520 ft^3/s) crossing from Agency Lake into Tulana on the northern shoreline. Figure 10 shows the location and number of each shoreline section along the Tulana side of the property. The majority of flow crosses the shoreline from Tulana to Upper Klamath Lake at sections 3 and 6. The majority of flow crosses the shoreline from Agency Lake into Tulana at sections 12, 13, and 16. Breaching the shoreline levee at these sections would open up the shoreline in a well spaced manner, as opposed to breaching the shoreline levees at sections 11, 12, and 13.

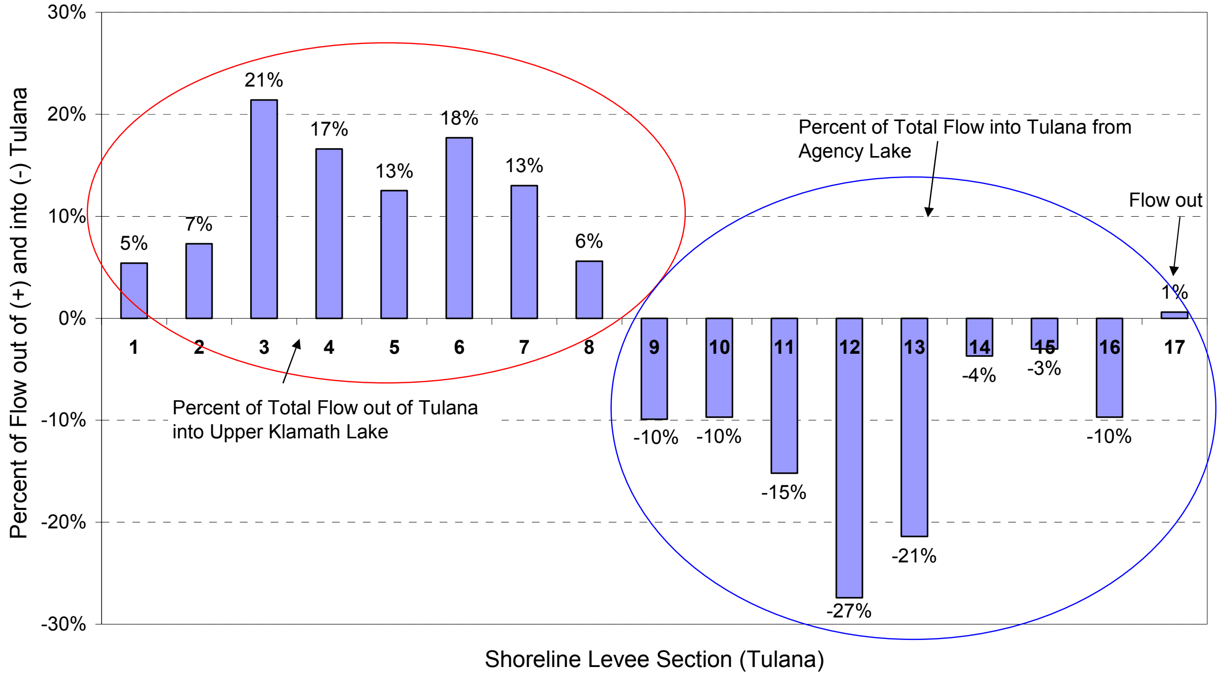

Figure 18. Percentage (+) of total flow (1,820 ft^3/s) into Upper Klamath Lake from Tulana (circled in red) through each shoreline section, and percentage (-) of total flow (520 ft^3/s) from Agency Lake into Tulana (circled in blue) through each shoreline section. See figure 10 for location of shoreline sections.

The location of simulated interior levee breaches in Goose Bay was determined in the same manner as for simulated river and shoreline levee breaches. Sections along the interior levees in Goose Bay were delineated (see figure 10), and the quantity of flow that crossed these sections in the base condition were measured. Figure 19 shows the location of interior levees selected for breaching in Goose Bay as determined by the following criteria.

- Maximize the amount of flow that would cross in the absence of the levees under the base condition.
- Avoid flow stagnation areas.
- Limit the length of levee breach segments to 250 meters.
- Locate interior levee breaches at areas of low floodplain/delta topography.

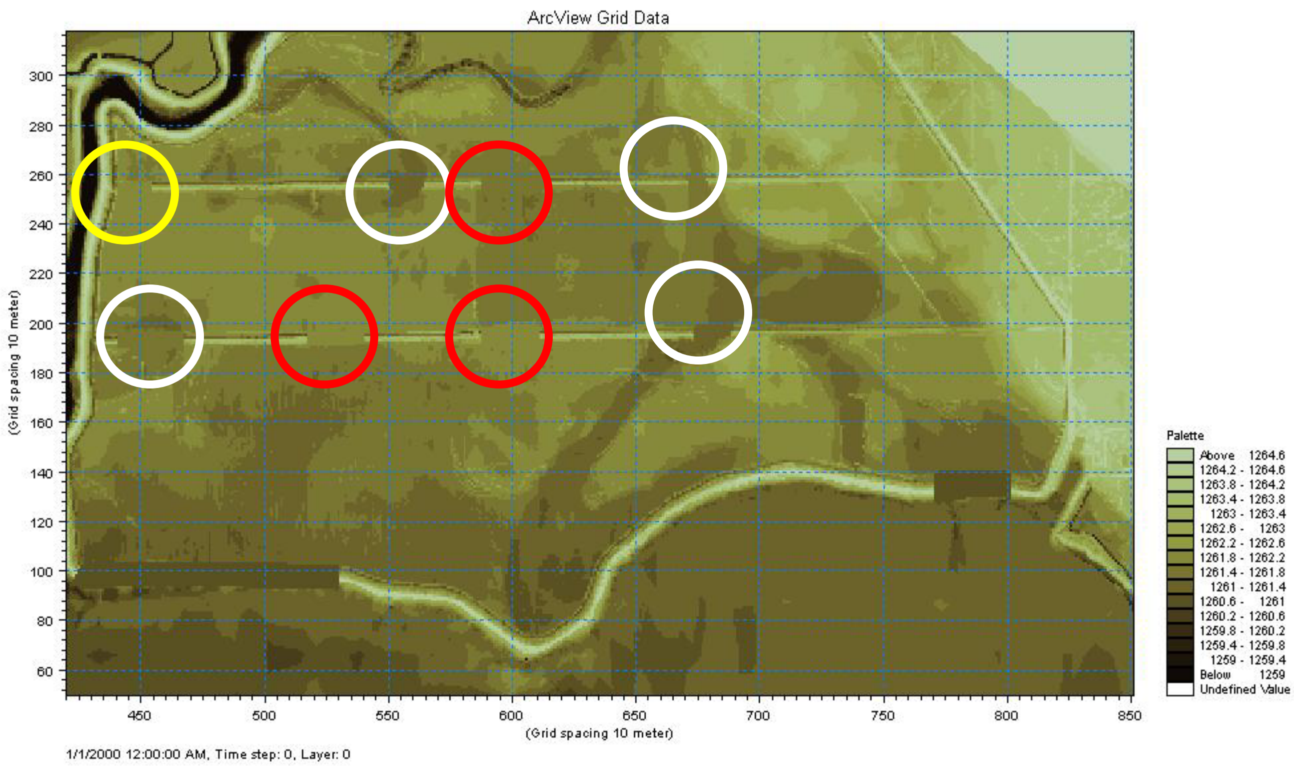

Figure 19. Location of simulated interior levee breaches in Goose Bay. Interior levee breaches were located to match old channels (circled in white), dominate flow area as determined by the base conditions (circled in red and limited to 250 m in length), and to avoid flow stagnation areas (circled in yellow).

On the Tulana side, interior levees only needed to be breached in one location where flow would be blocked (see figure 20). All other interior levees in Tulana exist at a low enough elevation that water can flow over them at lake levels greater than 4138 feet, which occurs most of the time. Therefore, it is not necessary to breach any other interior levees in Tulana in order for flow to reach Upper Klamath Lake or Agency Lake. However, the breaching of some interior levees in Tulana may help with flow circulation.

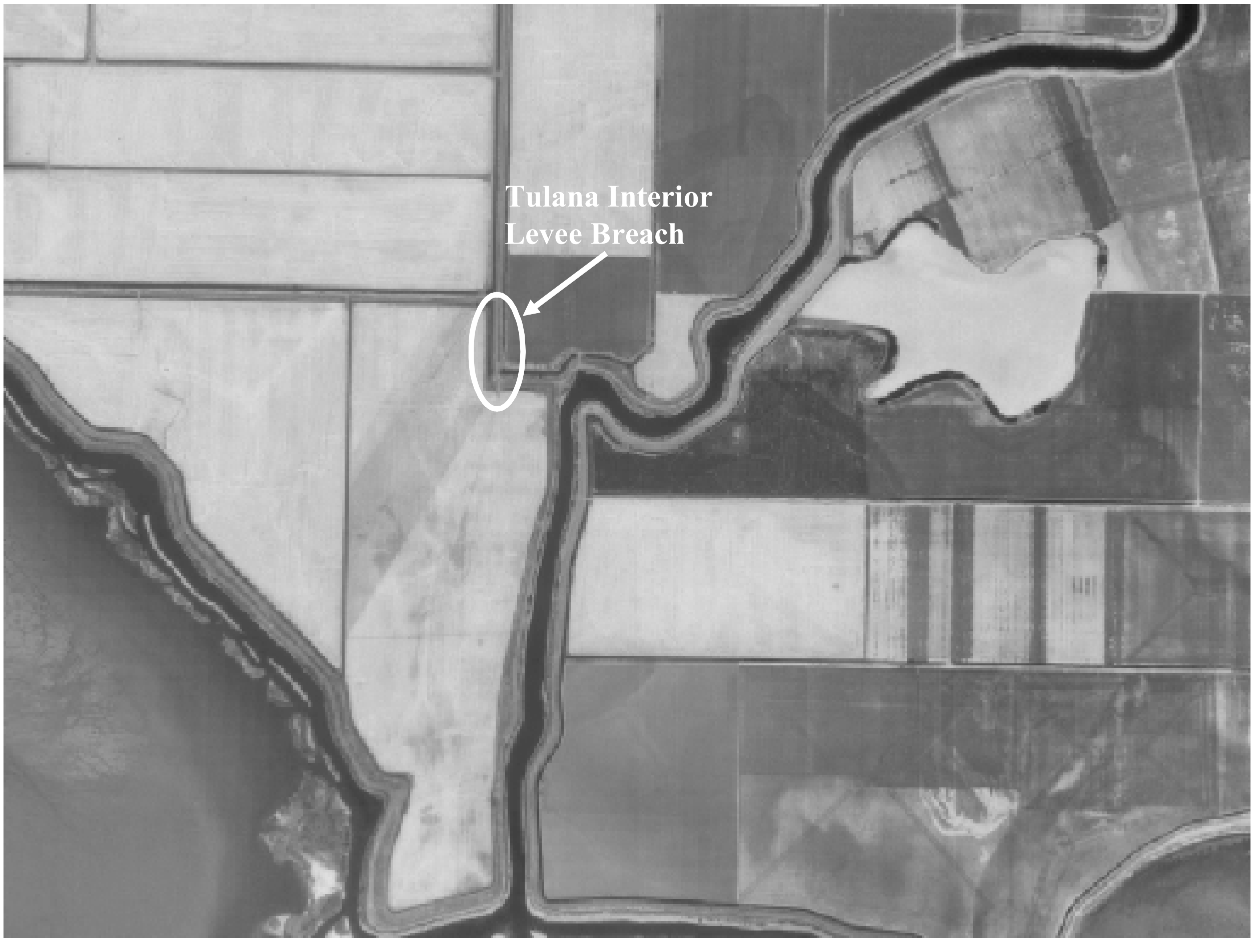

Figure 20. Location of simulated interior levee breach in Tulana.

5.3 Description of Model Results

Presentation of flow patterns across Goose Bay and Tulana is done by using velocity vector plots that are set on a color ramp background that represents water depth in the study area—as was the presentation of the results of the base condition in figure 15. The lengths of the vectors represent the magnitude (m/s) and direction of the velocity of flow. The largest velocities of the 100-year flood are plotted as a wider arrow. The background color represents the water depth (lighter blue is shallower water) over the floodplain/delta. Each plot has a reference vector plotted on the right side of the plot so that the magnitude of each vector can be estimated. Additionally, a legend showing the water depth color ranges is also located on the right side of each plot. All results from MIKE21 are presented in SI units. From these plots, it is possible to quickly assess flow through the floodplain/delta for each simulation. A pie chart that represents the percentage of flow (as a percentage of the total river flow for the particular simulation) that gets overbank through levee breaches on each side of the river is presented for each simulation. This allows for the assessment of quantitative changes in discharge through levee breaches for each simulation.

The results of the simulations presented in this study can serve as a guide to the design and location of levee breaches in the study area. The exact length and location of the actual levee breaches could be different. The number of levee breaches, and their approximate length and location, are more important than the exact details.

5.4 Key Modeled Scenarios

Several alternate scenarios were set up as model runs to simulate flow in the study area with levees removed at various locations along the river and shorelines of Goose Bay and Tulana (summarized in table 1). These scenarios were chosen by TNC in order to represent a range of possible alternatives for restoration of the Williamson River Floodplain/Delta. The set up and results for each scenario are presented below.

5.4.1 Reference Scenario

A reference scenario was modeled with the levee breaches as shown in figure 21, a river flow of 2,070 ft^3/s, a flow from Agency Lake of 745 ft^3/s, and a lake water surface elevation of 4143 feet. Figure 22 shows the vector plot of the results of this simulation, and figure 23 shows the percentage of flow through the river levee breaches.

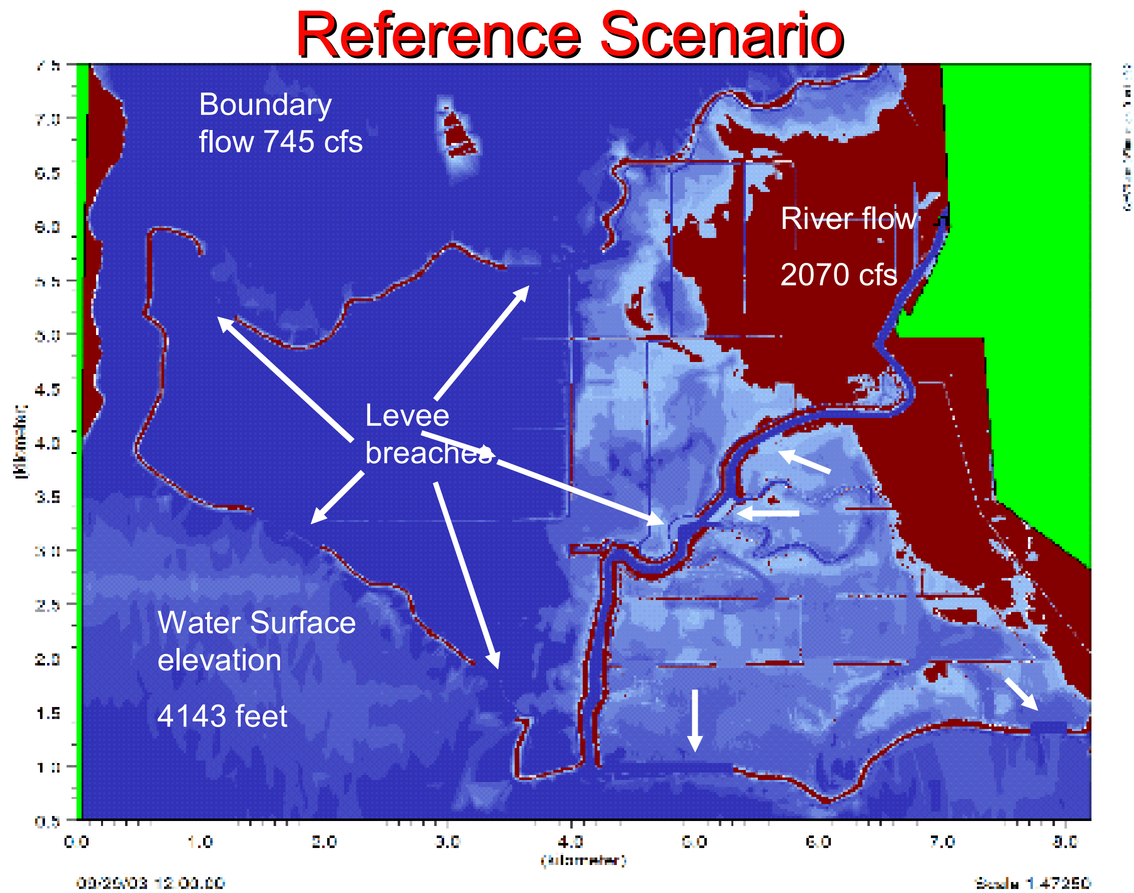

Figure 21. Location of river and shoreline levee breaches and boundary conditions for the reference scenario. Initial water surface was 4143 feet.

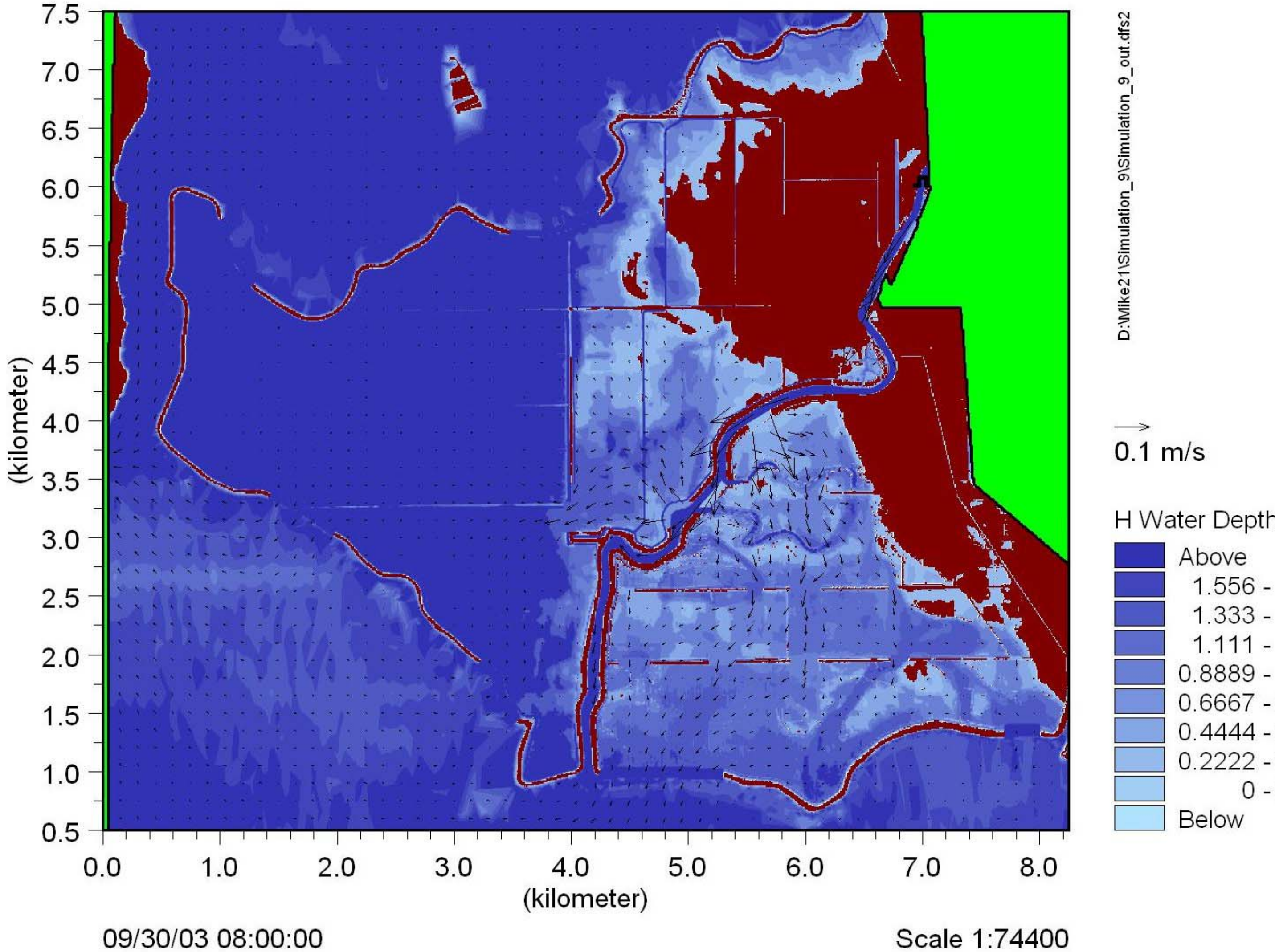

Figure 22. Velocity vector plot showing magnitude (m/s) of the velocity of flow and direction of flow through the study area for the reference scenario simulation. Water depth is represented by the background color, dark blue is deeper water than light blue.

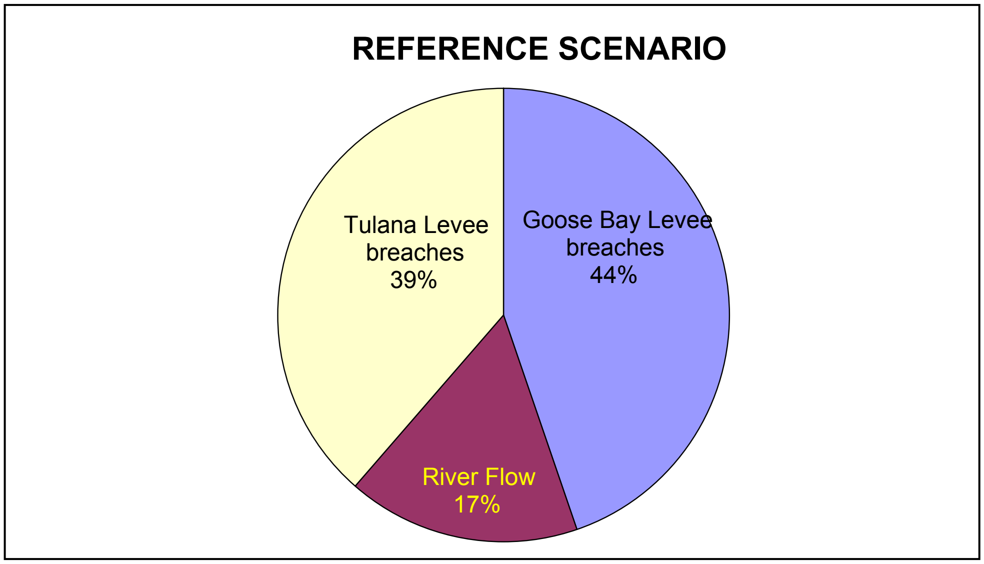

Figure 23. Flow distribution for the reference scenario: Percentage of total river flow (2,070 ft^3/s) through river levee breaches to Tulana and Goose Bay, and the percentage of total flow through the river channel at the mouth of the Williamson River into Upper Klamath Lake.

5.4.2 River Mouth Restoration Scenario

Under this model scenario, river, shoreline, and interior breaches are the same as in the reference scenario described in section 5.4.1. In addition, river levees were breached in the lower part of the river, shoreline levees were breached extending from the breach at section 3 along the shoreline of Tulana to the river mouth, and a channel was excavated from the new river levee breach in a southwest direction to Upper Klamath Lake. These changes are shown in figures 24 and 25. Figure 24 shows the topography of the river mouth under the reference scenario, and figure 25 shows the topography of the river mouth for the river mouth restoration scenario. Darker colors represent lower elevations and lighter colors represent higher elevations (in meters). Figure 26 shows the vector plot of the results of this simulation, and figure 27 shows the percentage of flow through the river levee breaches.

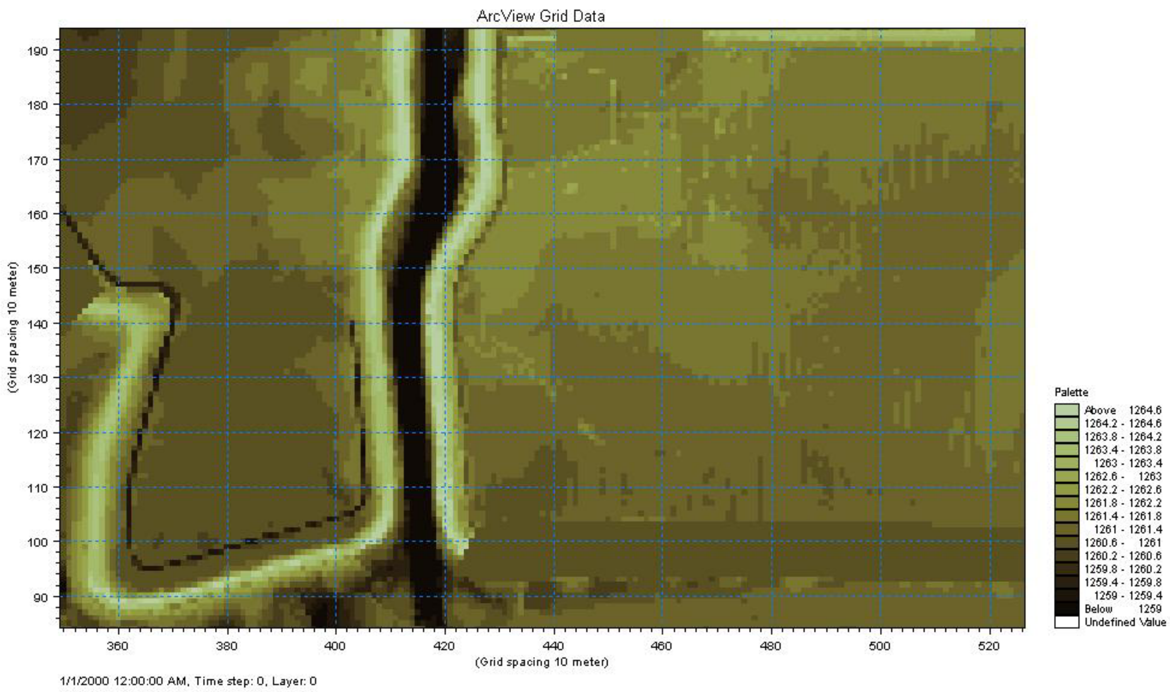

Figure 24. Representation of the topography near the river mouth under the reference scenario. Levees are visible as lighter colors.

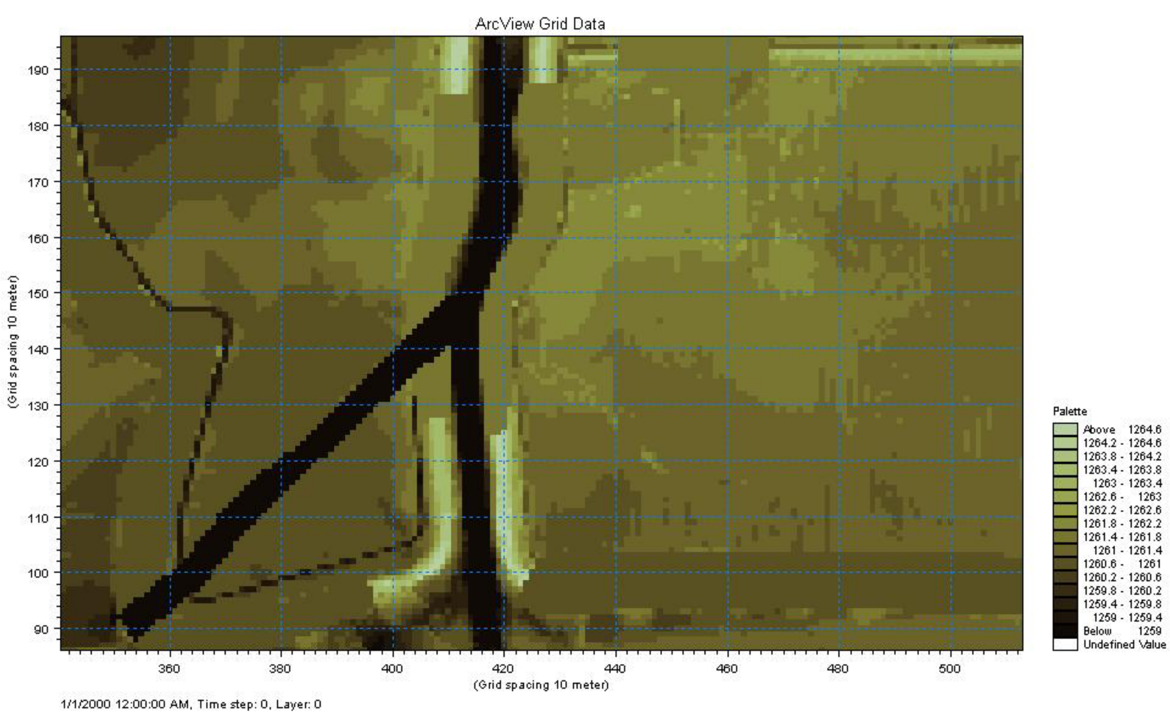

Figure 25. Representation of the topography near the river mouth under the river mouth restoration scenario. Levees are visible as lighter colors and the simulated channel excavation is visible as the darker strip extending from the existing river channel to Upper Klamath Lake.

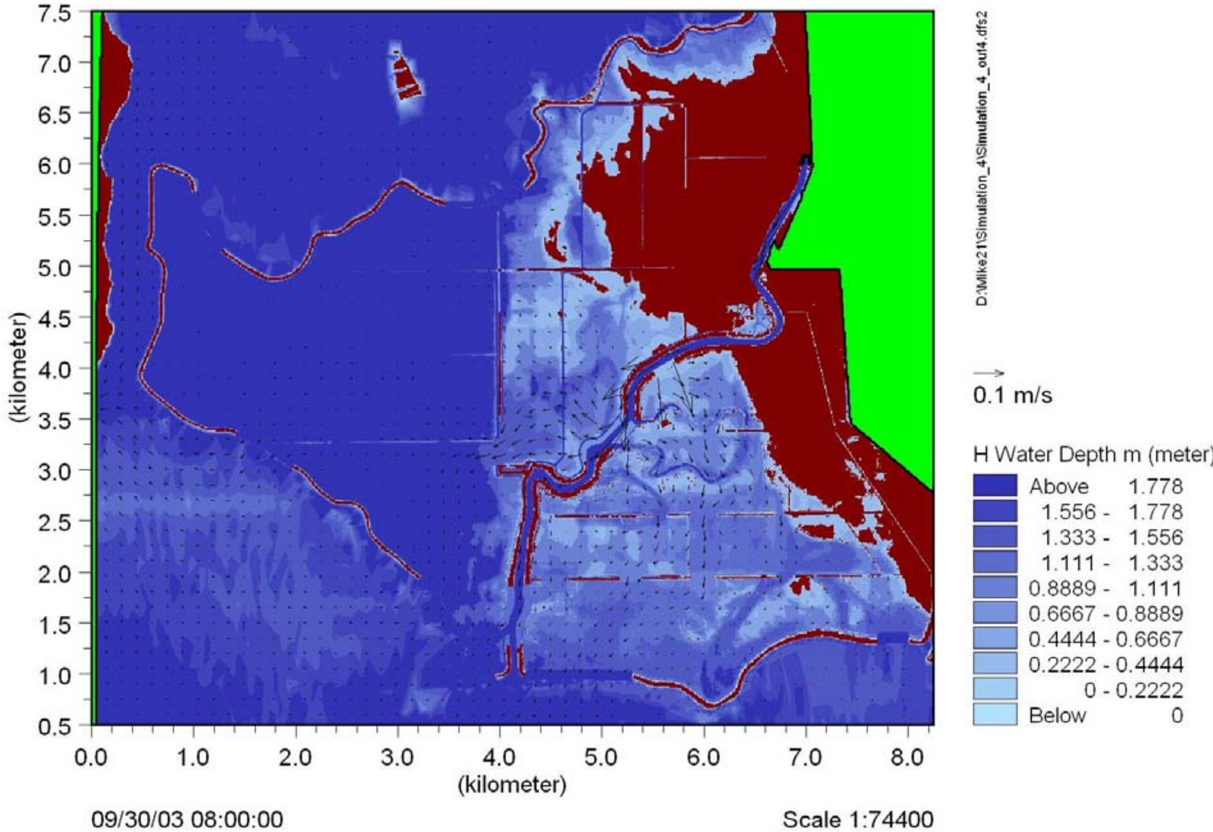

Figure 26. Velocity vector plot showing magnitude (m/s) of the velocity of flow and direction of flow through the study area for the river mouth restoration scenario simulation. Water depth is represented by the background color; dark blue is deeper water than light blue.

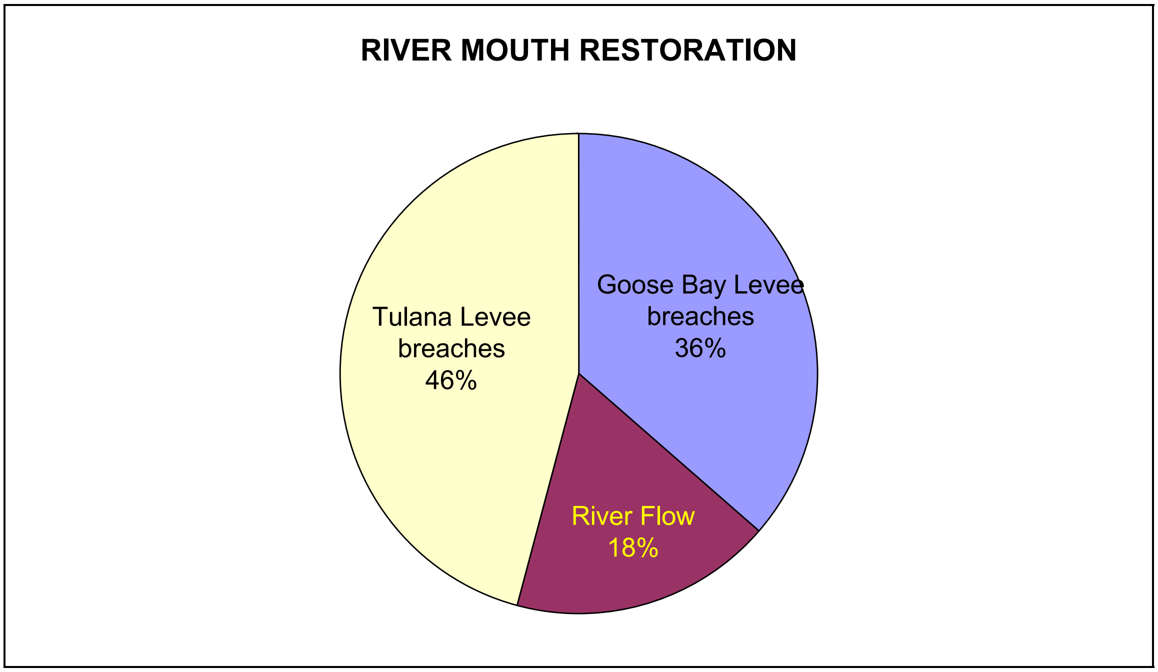

Figure 27. Flow distribution for the river mouth restoration scenario: Percentage of total river flow (2,070 ft^3/s) through river levee breaches to Tulana and Goose Bay, and the percentage of total flow through the river channel at the mouth of the Williamson River into Upper Klamath Lake.

5.4.3 Reference Scenario without connection to Agency Lake

Under this scenario, all levee breaches and boundary conditions are the same as in the reference scenario described in section 5.4.1 with the exception that shoreline levees are not breached along Agency Lake (see figure 28). Figure 29 shows the vector plot of the results of this simulation, and figure 30 shows the percentage of flow through the river levee breaches.

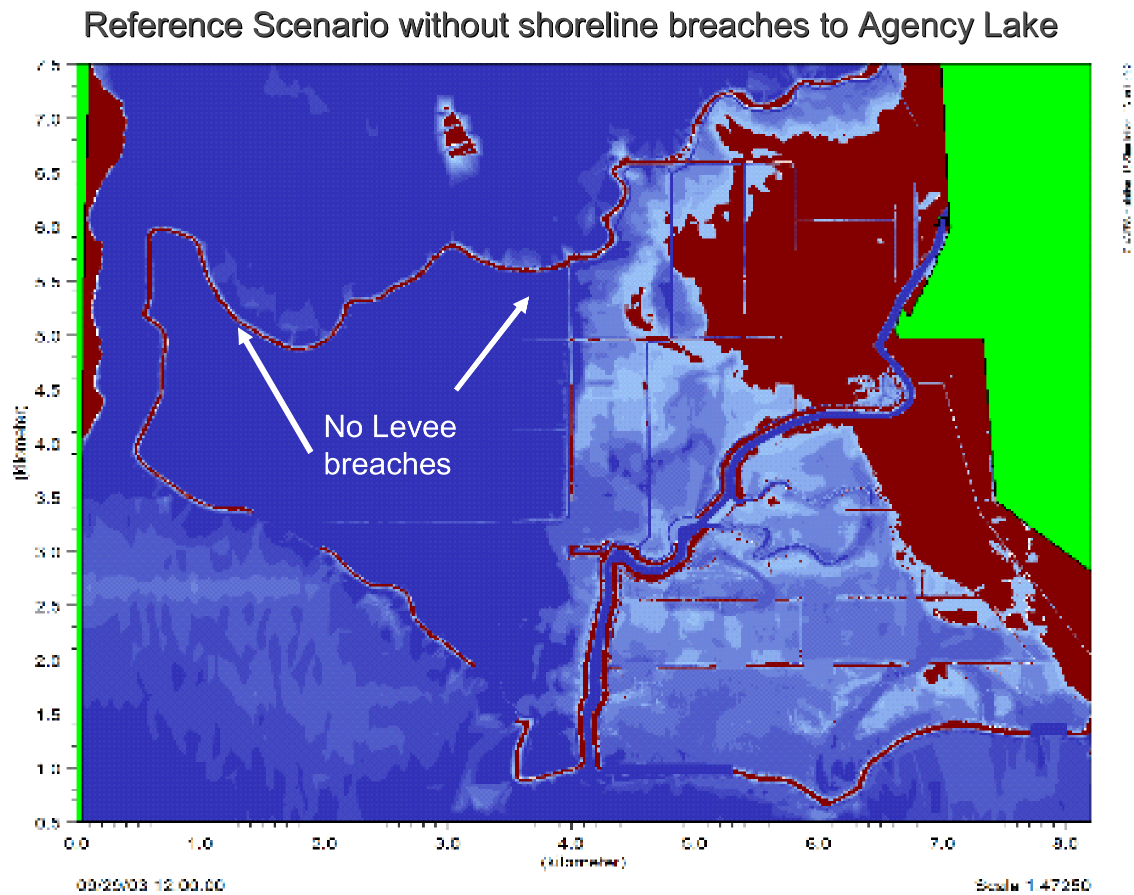

Figure 28. Location of river and shoreline levee breaches and boundary conditions for the reference scenario without connection to Agency Lake. Initial water surface was 4143 feet.

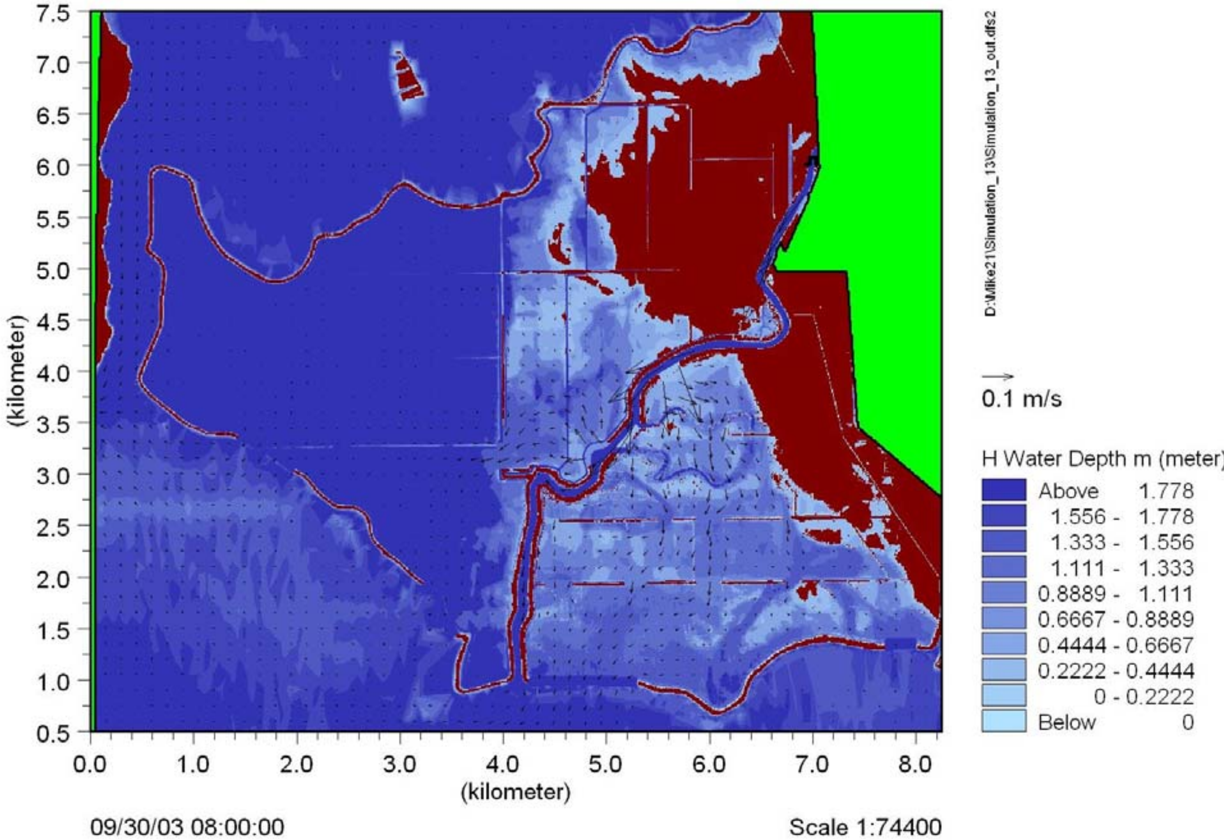

Figure 29. Velocity vector plot showing magnitude (m/s) of the velocity of flow and direction of flow through the study area for the reference scenario without connection to Agency Lake simulation. Water depth is represented by the background color, dark blue is deeper water than light blue.

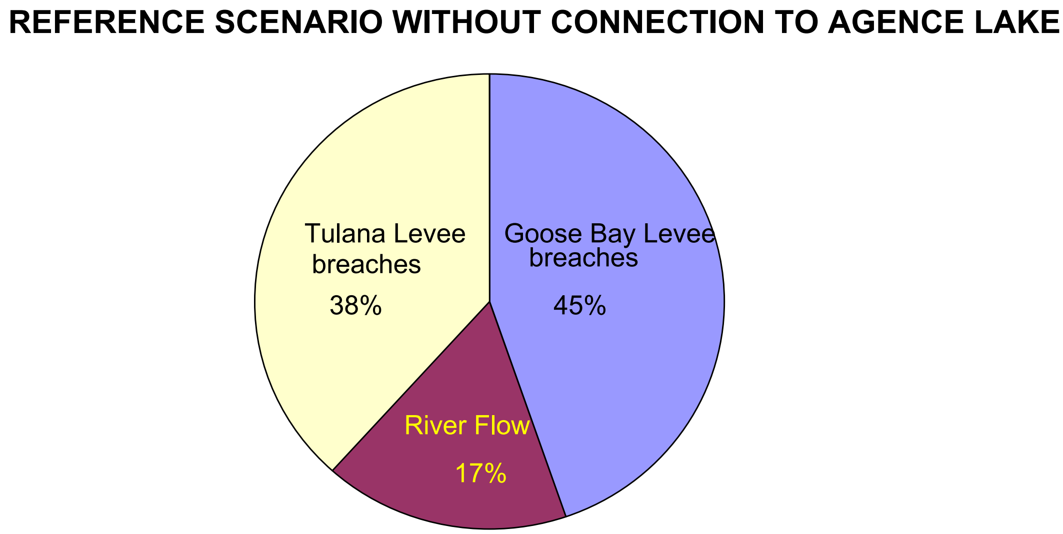

Figure 30. Flow distribution for the reference scenario without a connection to Agency Lake: Percentage of total river flow (2,070 ft^3/s) through river levee breaches to Tulana and Goose Bay, and the percentage of total flow through the river channel at the mouth of the Williamson River into Upper Klamath Lake.

5.4.4 Oxbow Channel Restoration Scenario

Under this scenario, river and shoreline breaches were the same as described for the reference scenario in section 5.4.1. The primary focus of this scenario was to simulate the restoration of the oxbow that was present in the 1940-41 photographs thus restoring a major component of the historic channel alignment. Figure 31 shows the existing topography of the oxbow region of the study area. The oxbow channel restoration involves a simulated re-excavation of the oxbow channel. The oxbow channel was re-excavated down to an elevation of 4136 feet to insure that a surface water connection with the main channel is maintained at all times. Two alternatives of this scenario were simulated. Scenario 1 is where the existing main channel is filled in between the entrance and exit to the oxbow channel (see figure 32). Scenario 1 includes restoration of the river mouth. Scenario 2 does not include the filling of the main channel near the old oxbow (see figure 33) and is done without restoration of the river mouth. Figures 34 and 36 show the vector plots of the results of scenario 1 and scenario 2, respectively, and figures 35 and 37 show the percentage of flow through the river levee breaches of scenario 1 and scenario 2 respectively.

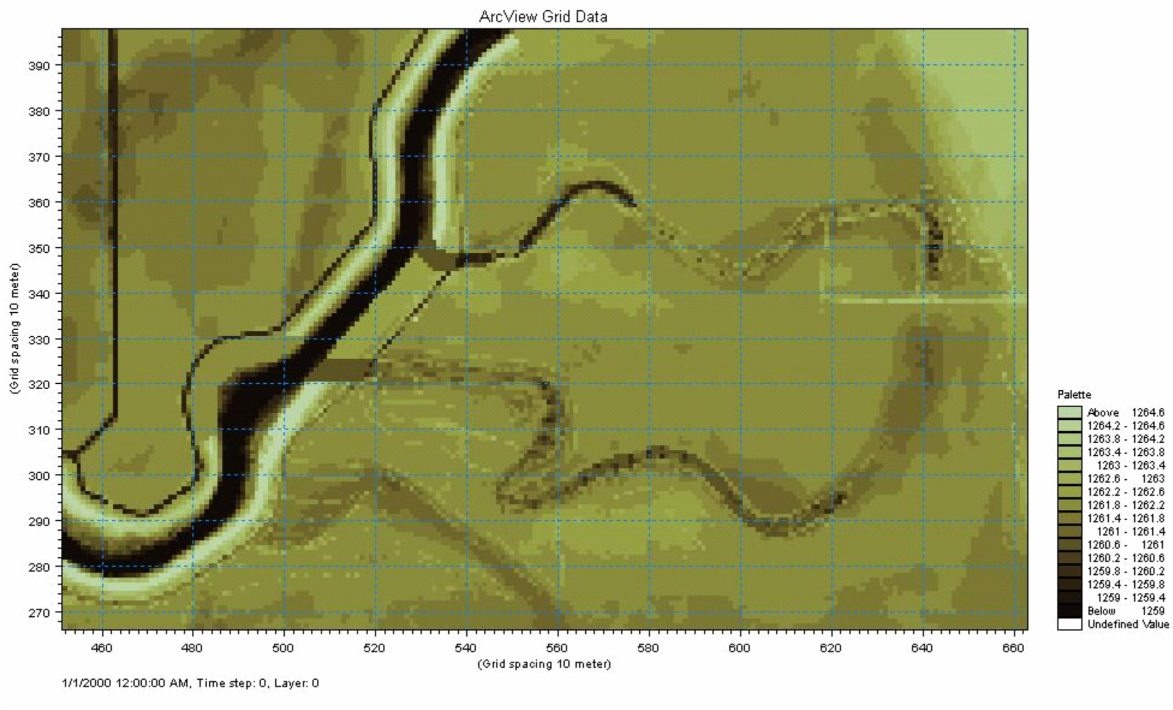

Figure 31. Existing topography of the oxbow region of the study area. Darker colors are lower elevations and lighter colors are higher elevations.

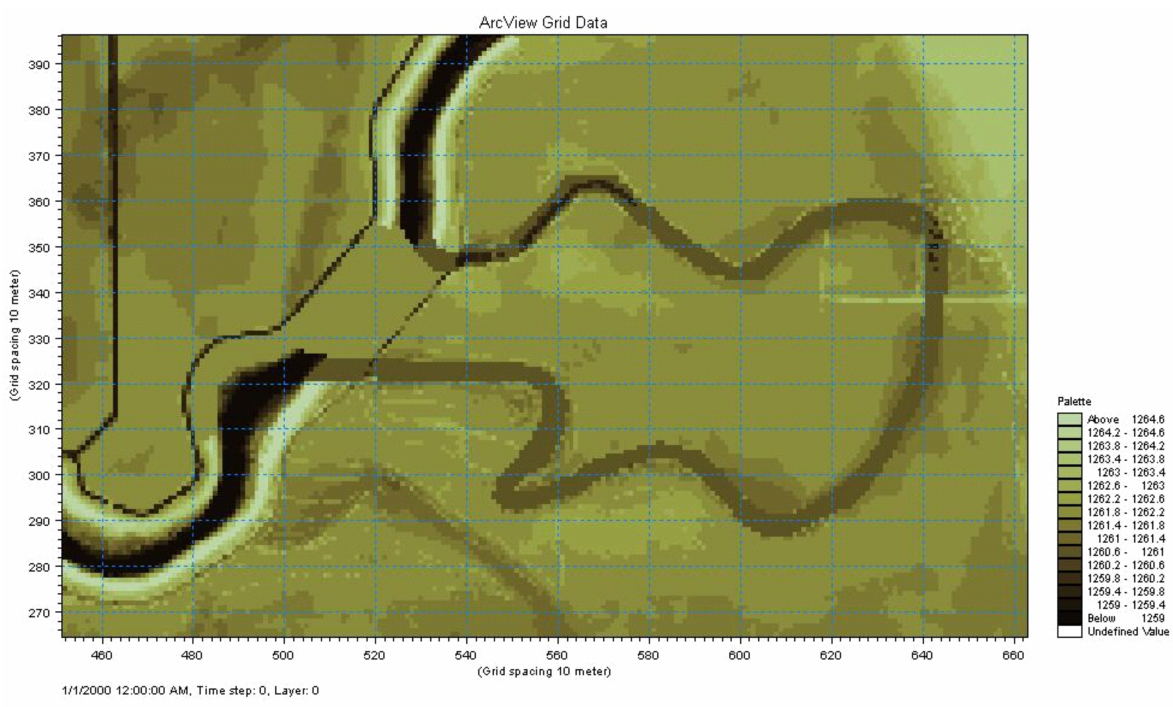

Figure 32. Topography of the oxbow region of the study area under the oxbow channel restoration scenario 1, which includes filling of the main channel between the entrance and exit of the re-excavated oxbow channel. Darker colors are lower elevations and lighter colors are higher elevations.

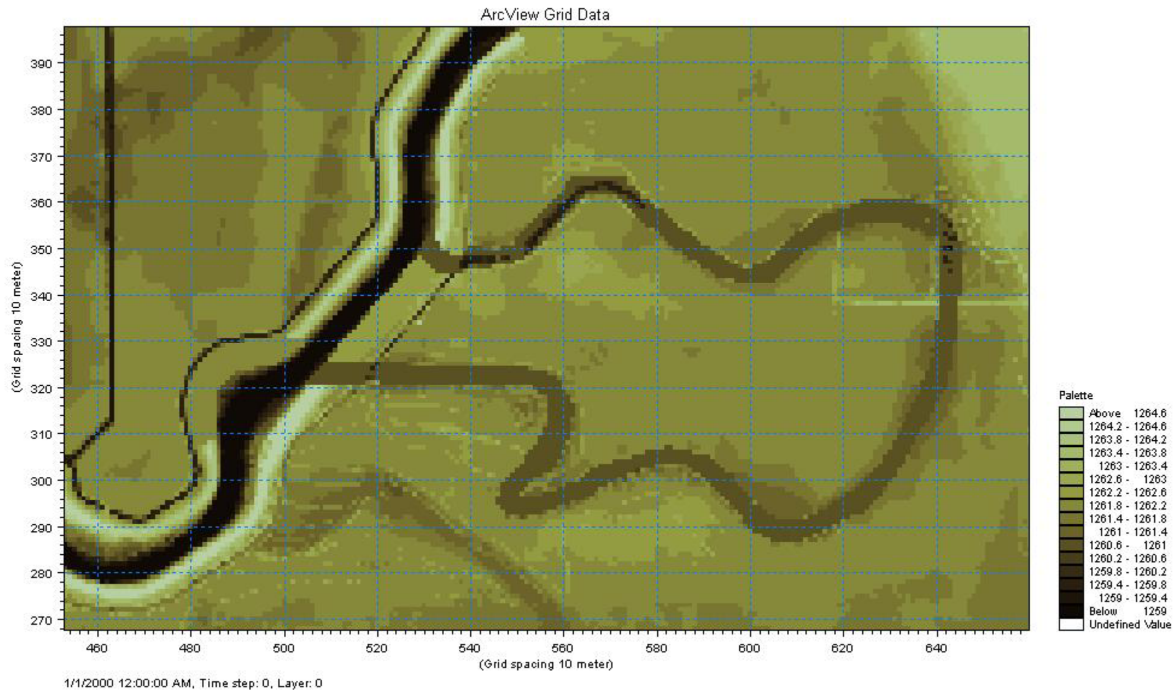

Figure 33. Topography of the oxbow region of the study area under the oxbow channel restoration scenario 2. This scenario does not include filling of the main channel between the entrance and exit of the re-excavated oxbow channel and does not include the river mouth restoration. Darker colors are lower elevations and lighter colors are higher elevations.

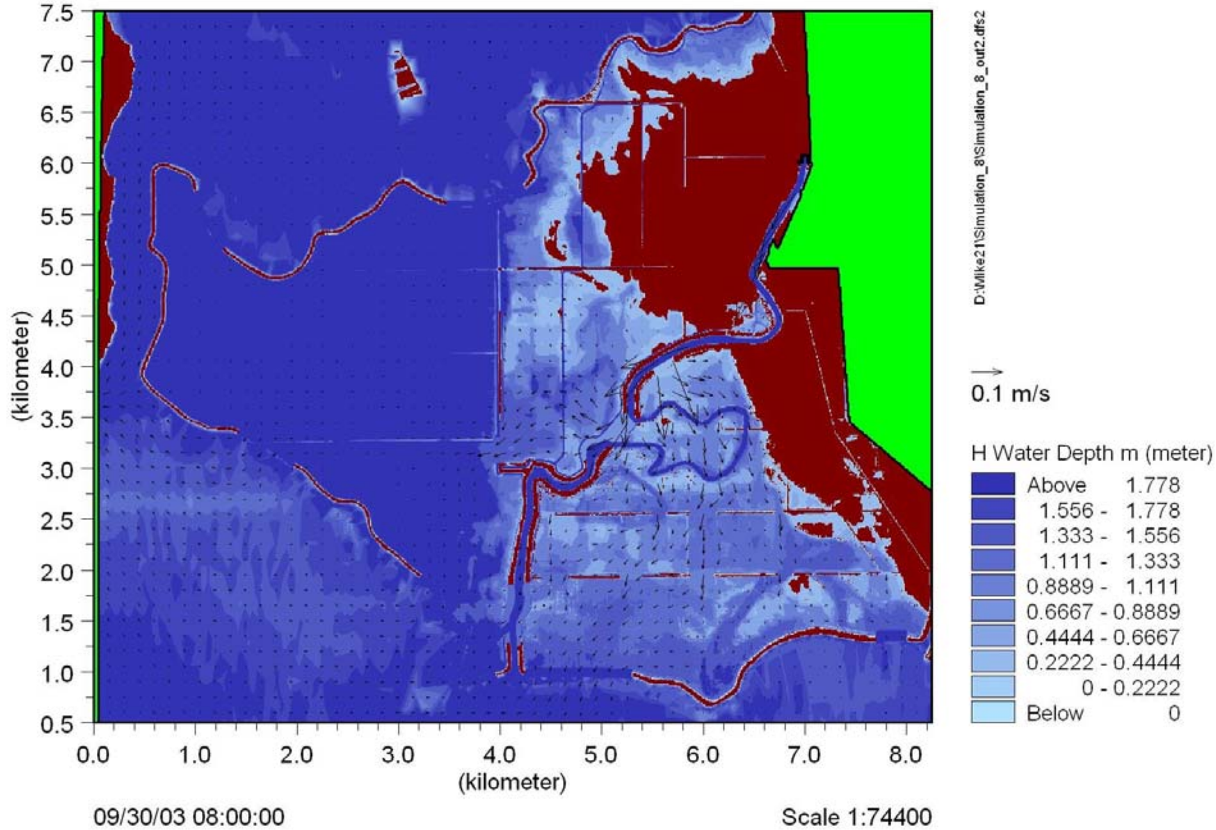

Figure 34. Velocity vector plot showing magnitude (m/s) of the velocity of flow and direction of flow through the study area for the oxbow channel restoration scenario 1 simulation. Water depth is represented by the background color, dark blue is deeper water than light blue.

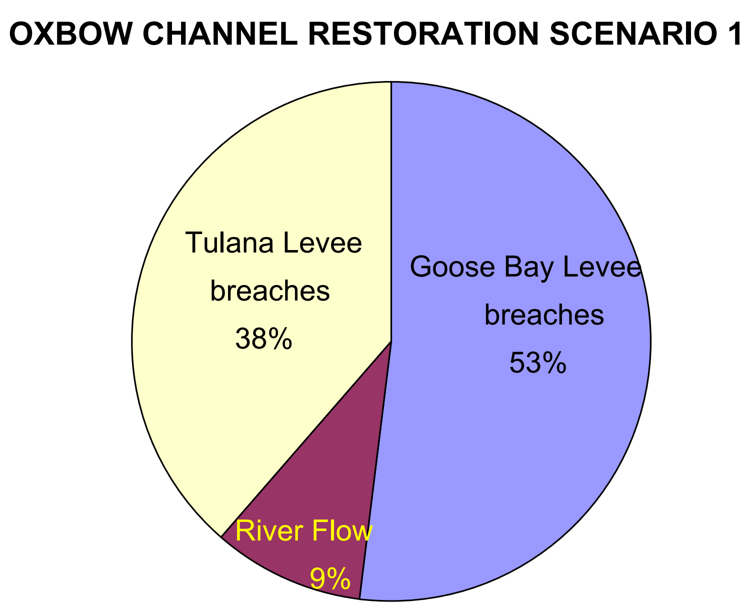

Figure 35. Flow distribution for the oxbow channel restoration scenario 1: Percentage of total river flow

(2,070 ft^3/s) through river levee breaches to Tulana and Goose Bay, and the percentage of total flow through the river channel at the mouth of the Williamson River into Upper Klamath Lake.**

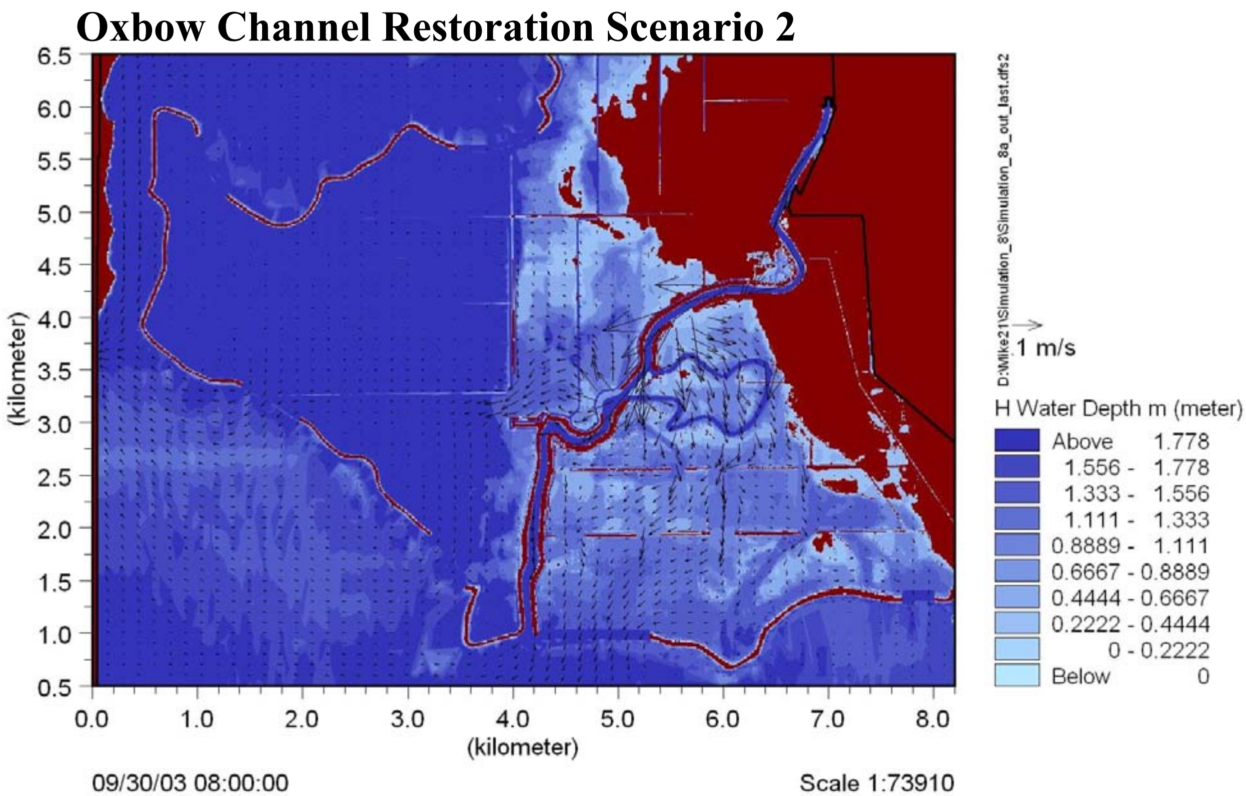

Figure 36. Velocity vector plot showing magnitude (m/s) of the velocity of flow and direction of flow through the study area for the oxbow channel restoration scenario 2 simulation. Water depth is represented by the background color, dark blue is deeper water than light blue.

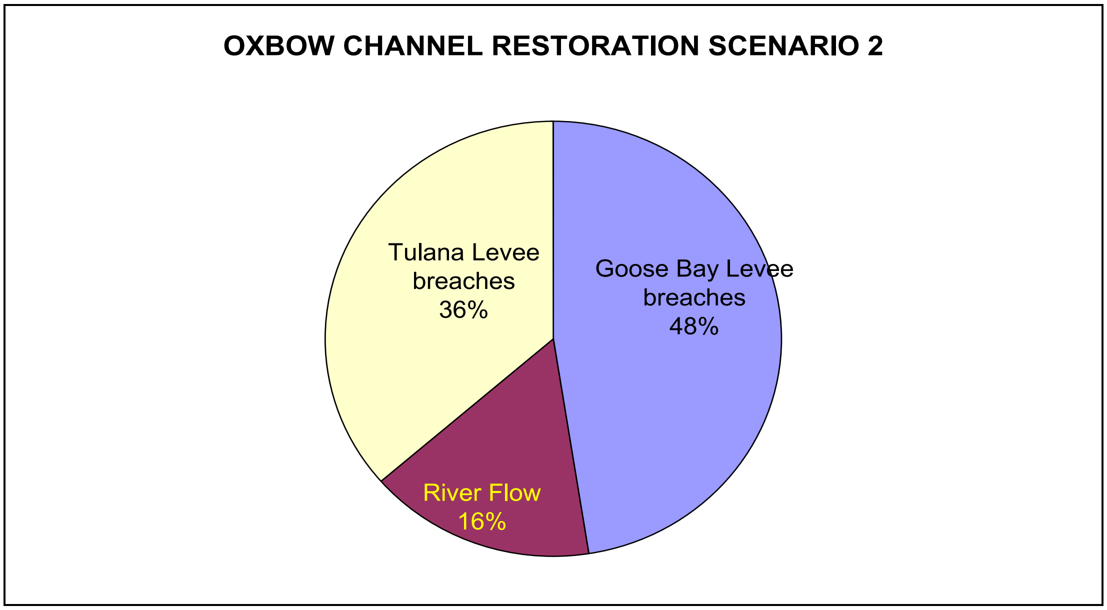

Figure 37. Flow distribution for the oxbow channel restoration scenario 2: Percentage of total river flow (2,070 ft^3/s) through river levee breaches to Tulana and Goose Bay, and the percentage of total flow through the river channel at the mouth of the Williamson River into Upper Klamath Lake.

5.4.5 Narrowed Channel Scenario

Under this scenario, all river and shoreline levee breaches, boundary conditions, and initial conditions are the same as in the reference scenario described in section 5.4.1. In addition, the main channel is narrowed by one fourth to one third beginning just downstream of the oxbow channel. Figure 38 shows the channel banks and width of the river just downstream of the oxbow under existing conditions and figure 39 shows the simulated narrowing of the river channel. The simulated narrowing was done using the grid editor in MIKE21. The number of 10 meter grid cells across the channel was counted and 1/3 of them were raised to an elevation matching the adjacent floodplain/delta land surface elevation. If there were 9 grid cells across the channel, then 3 grid cells were "filled in." However, if the number of grid cells across the channel were not divisible by 3, less than 1/3 of the grid cells were "filled." For example, if there were 8 grid cells across the channel, 2 grid cells were filled. Hence, channel narrowing was on the order of 1/4 to 1/3. Figure 40 shows the vector plot of the results of this simulation, and figure 41 shows the percentage of flow through the river levee breaches.

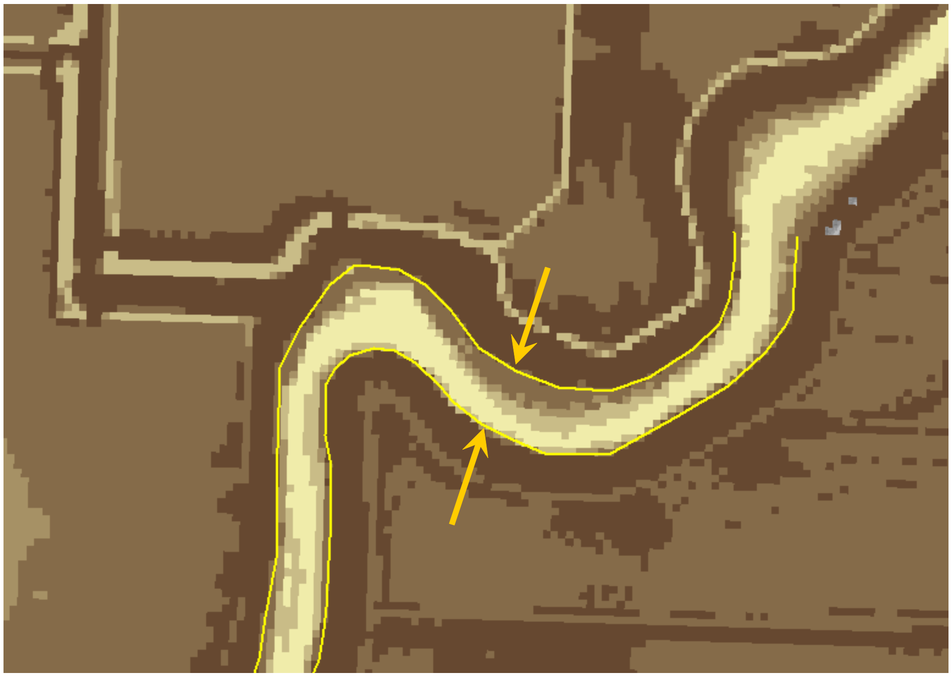

Figure 38. Yellow lines highlight the existing channel width in a reach of the river just downstream of the oxbow.

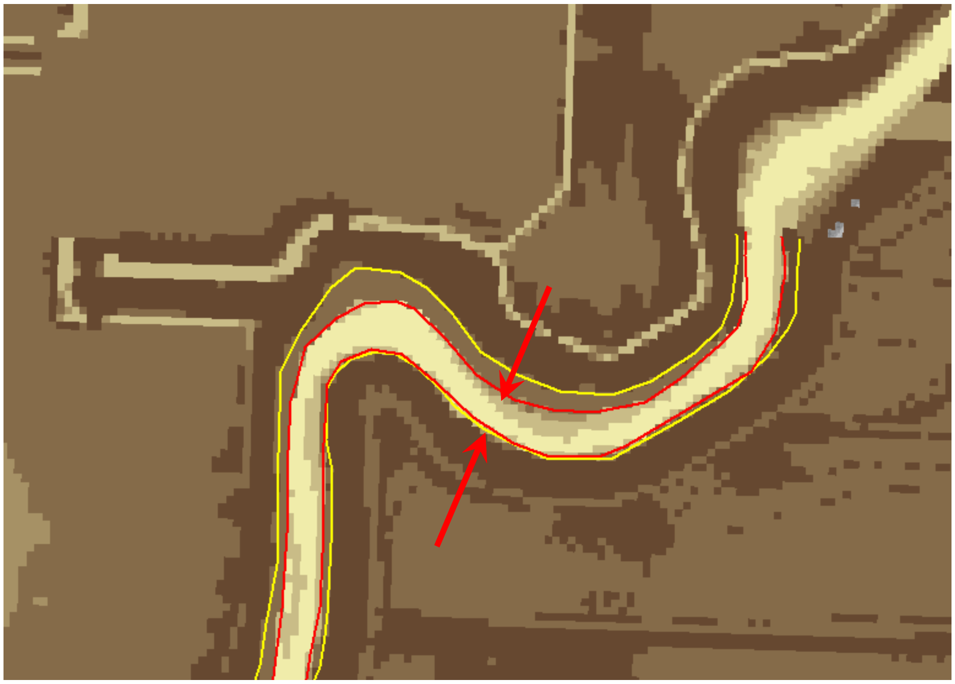

Figure 39. Red lines highlight the simulated channel narrowing in relation to the channel width under existing conditions (yellow line).

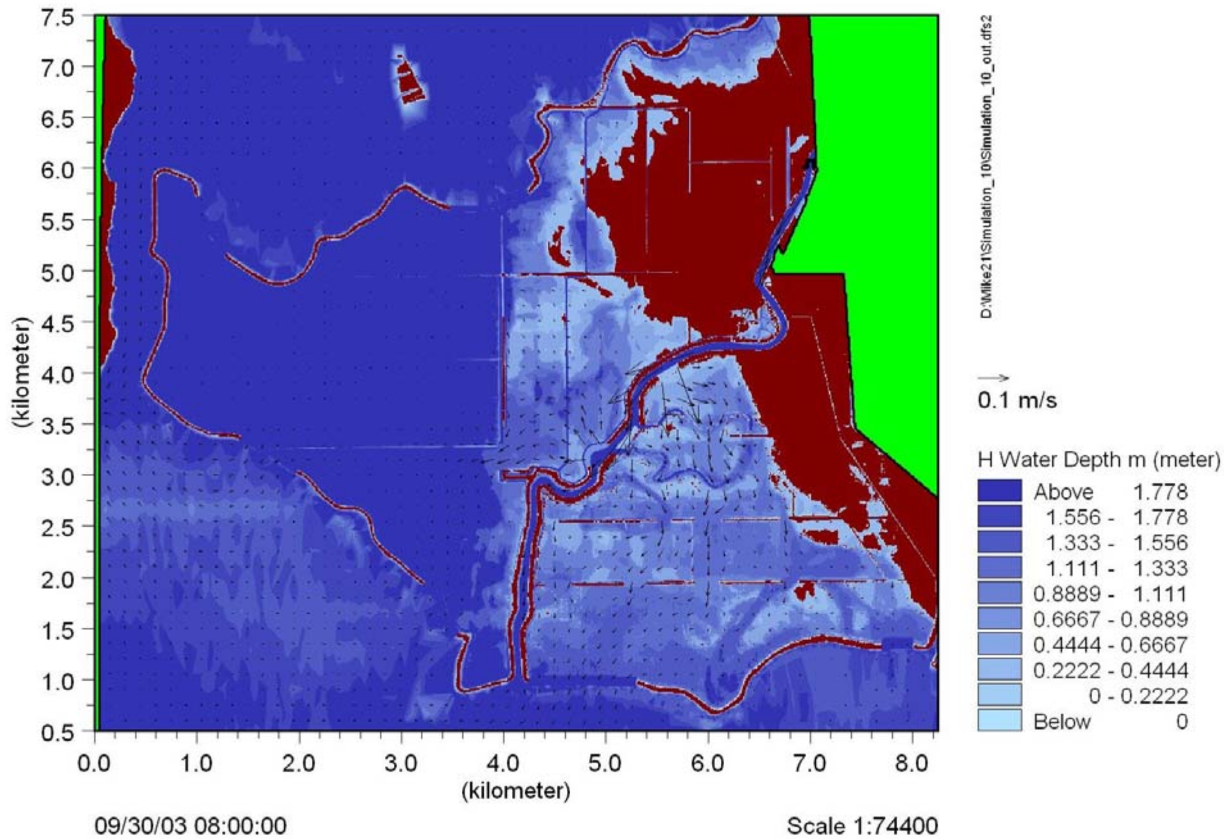

Figure 40. Velocity vector plot showing magnitude (m/s) of the velocity of flow and direction of flow through the study area for the narrowed channel restoration scenario simulation. Water depth is represented by the background color, dark blue is deeper water than light blue.

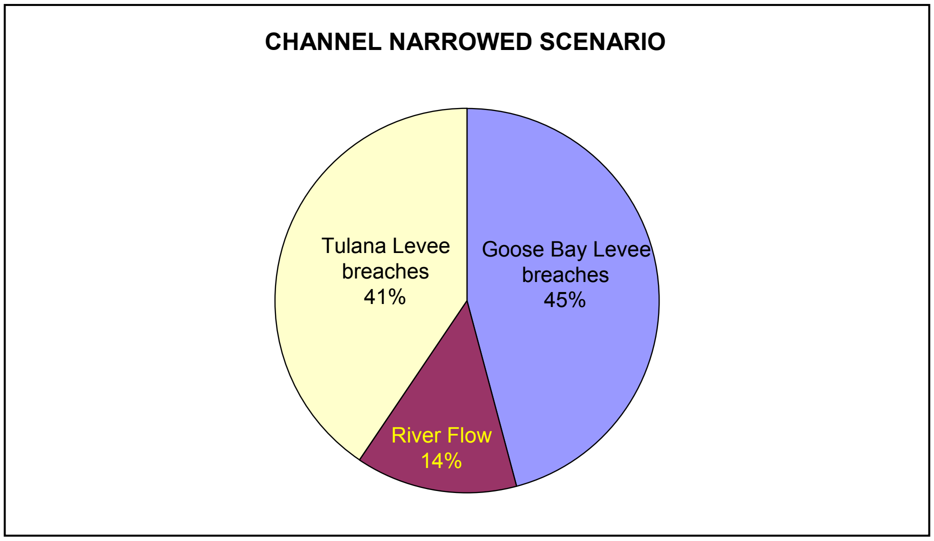

Figure 41. Flow distribution for the channel narrowed scenario: Percentage of total river flow (2,070 ft^3/s) through river levee breaches to Tulana and Goose Bay, and the percentage of total flow through the river channel at the mouth of the Williamson River into Upper Klamath Lake.

5.4.6 100-year Flood, Low Lake Elevation Scenario

Under this simulation, river and shoreline levee breaches are the same as in the reference scenario described in section 5.4.1. The 100-year flood peak is estimated at 16,000 ft^3/s and is used as an upstream boundary condition of constant flow from the Williamson River. The 100-year flood peak is nearly eight times greater than the 1.5-year flood peak. The flow rate from Agency Lake was increased some, but not so much that it would represent 18 percent of the total flow into Upper Klamath Lake during the 100-year flood from the Williamson River. Sufficient data were not available from the Wood River and Seven Mile River to establish the likelihood that, during high flows, the same proportion holds between flow from Agency Lake and the Williamson River. Therefore, the upstream, boundary condition of flow from Agency Lake was set equal to a constant value of 1,415 ft^3/s, which is approximately twice as much flow from Agency Lake as in the reference scenario. This was done to simulate Agency Lake as a large body of water with a net flow toward Upper Klamath Lake that is not overwhelmed by any northward flow from the Williamson River. The absence of data on flow rate, pattern.and timing in Agency Lake precludes a more precise representation of flow from this area. The downstream boundary and initial water surface elevation under this scenario were set at a low lake water surface elevation of 4140 feet. A low lake elevation is likely given that the most likely time period of occurrence of the 100-year flood is in December or early January (see figures 1 and 3). Figure 42 shows the vector plot of the results of this simulation, and figure 43 shows the percentage of flow through the river levee breaches.

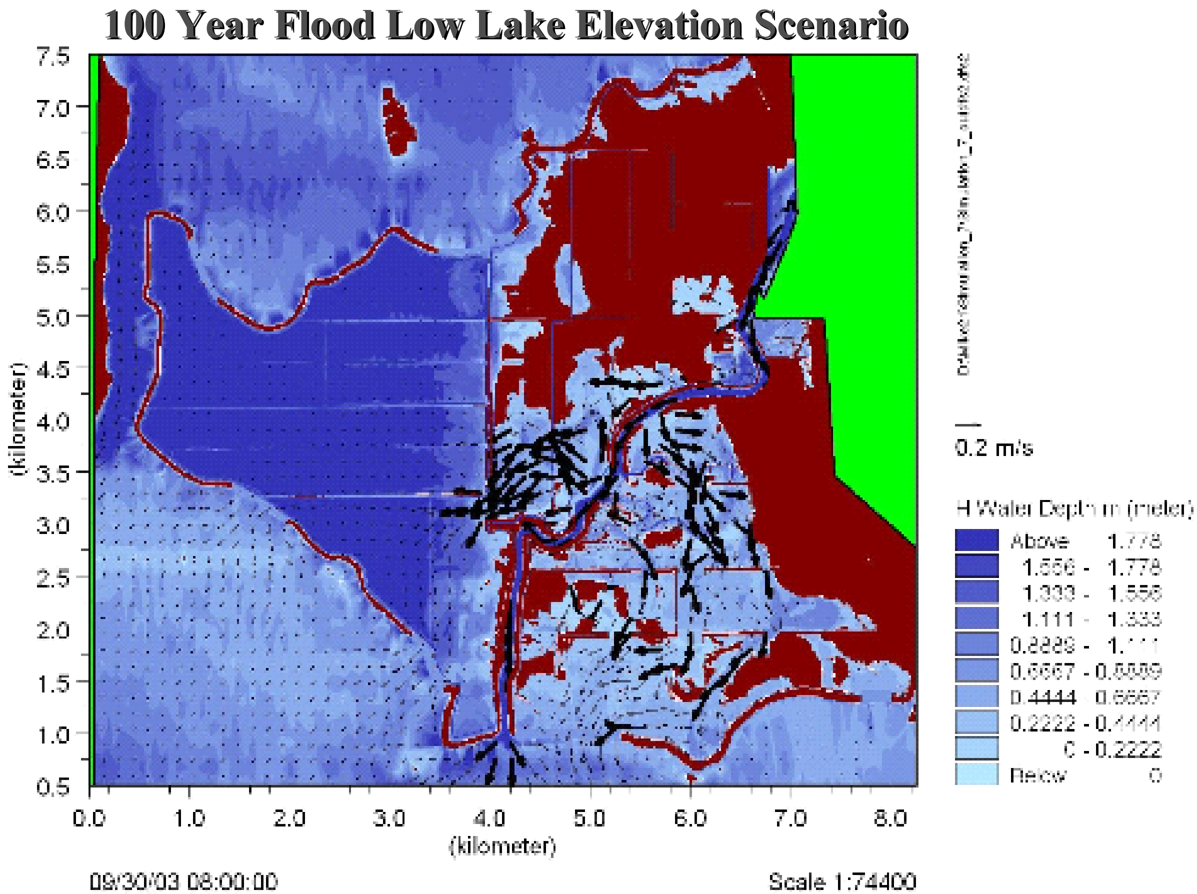

Figure 42. Velocity vector plot showing magnitude (m/s) of the velocity of flow and direction of flow through the study area for the 100-year flood scenario simulation. Water depth is represented by the background color, dark blue is deeper water than light blue.

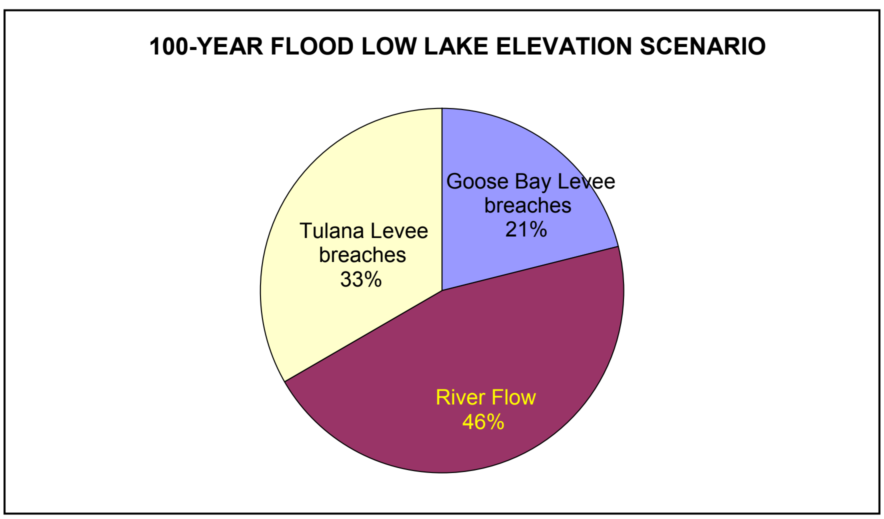

Figure 43. Flow distribution for the reference scenario during the 100-year flood peak and a low lake elevation of 4140 feet: Percentage of total river flow (16,000 ft^3/s) through river levee breaches to Tulana and

Goose Bay, and the percentage of total flow through the river channel at the mouth of the Williamson River into Upper Klamath Lake.

5.4.7 Average June Hydrologic Conditions Scenario

Under this scenario, the river and shoreline levee breaches are the same as in the reference scenario described in section 5.4.1. The upper boundary condition for flow in the Williamson River is set at the average of the median, mean daily flows for the month of June. Mean daily flow is the average flow rate for a given day. Mean daily flow data are available from the USGS for each day from the period 1917 to 2001. Therefore, each day of the year has a mean flow for each of the 86 years of record. The median, mean daily flow is the median value of the 86 flow values for each particular day. The median value represents a mean daily flow rate that occurs 1 out of every 2 years (see figure 3). For example, a median mean daily flow of 850 ft^3/s will occur at least every other year on June 15. Median mean daily flows decline throughout the month of June from over 1,100 ft^3/s to under 700 ft^3/s (figure 44). In order to capture a representative flow for June, the average of the median, mean daily flows, 847 ft^3/s, was used, which is close to the median, mean daily flow for the middle of June. To represent a typical lake water surface elevation in June, a water surface elevation of 4142.1 feet for the downstream boundaries and the initial water surface elevation were used. This elevation is based on the Upper Klamath Lake end-of-month minimum elevations for a "Below Average" water year type, as stated in the U.S. Fish and Wildlife Service's Biological Opinion on the 10-year operation plan for the Klamath Project (U.S. Fish and Wildlife Service, 2002).

Figure 45 shows the vector plot of the results of this simulation, and figure 46 shows the percentage of flow through the river levee breaches. Note that no flow gets out of bank through the upstream river levee breach on the Goose Bay side of the river.

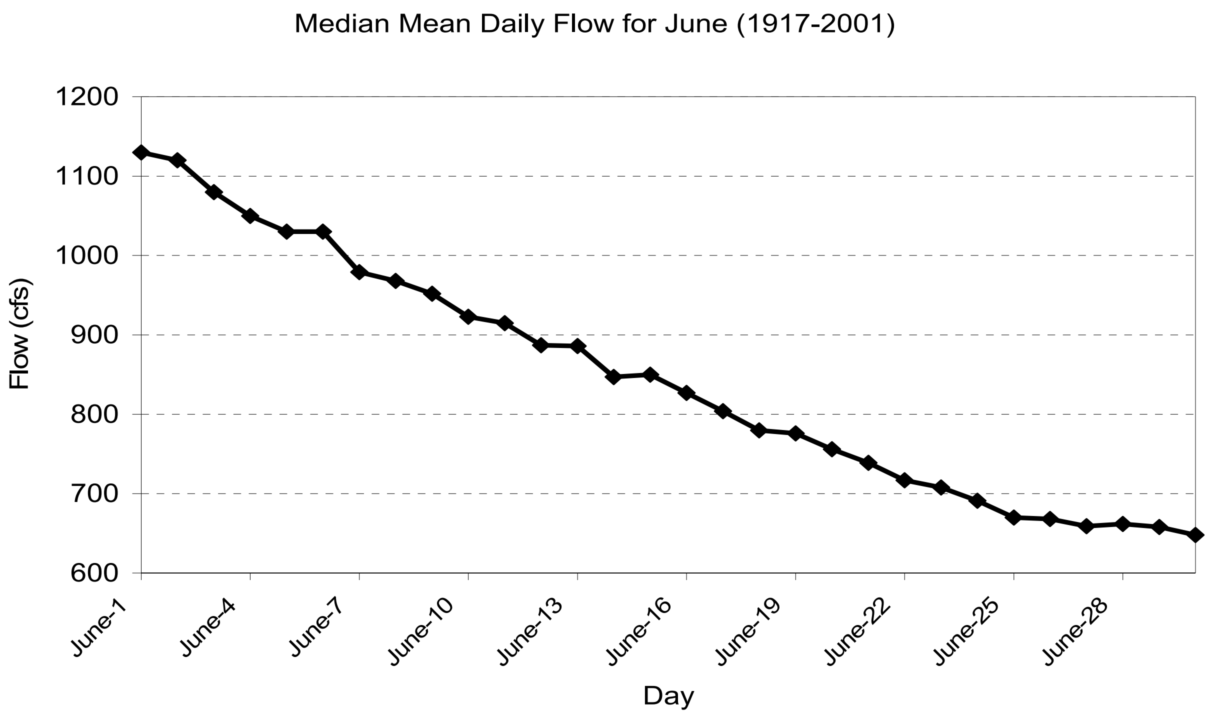

Figure 44. Median mean daily flow for each day in the month of June over the period of record (1917-2001).

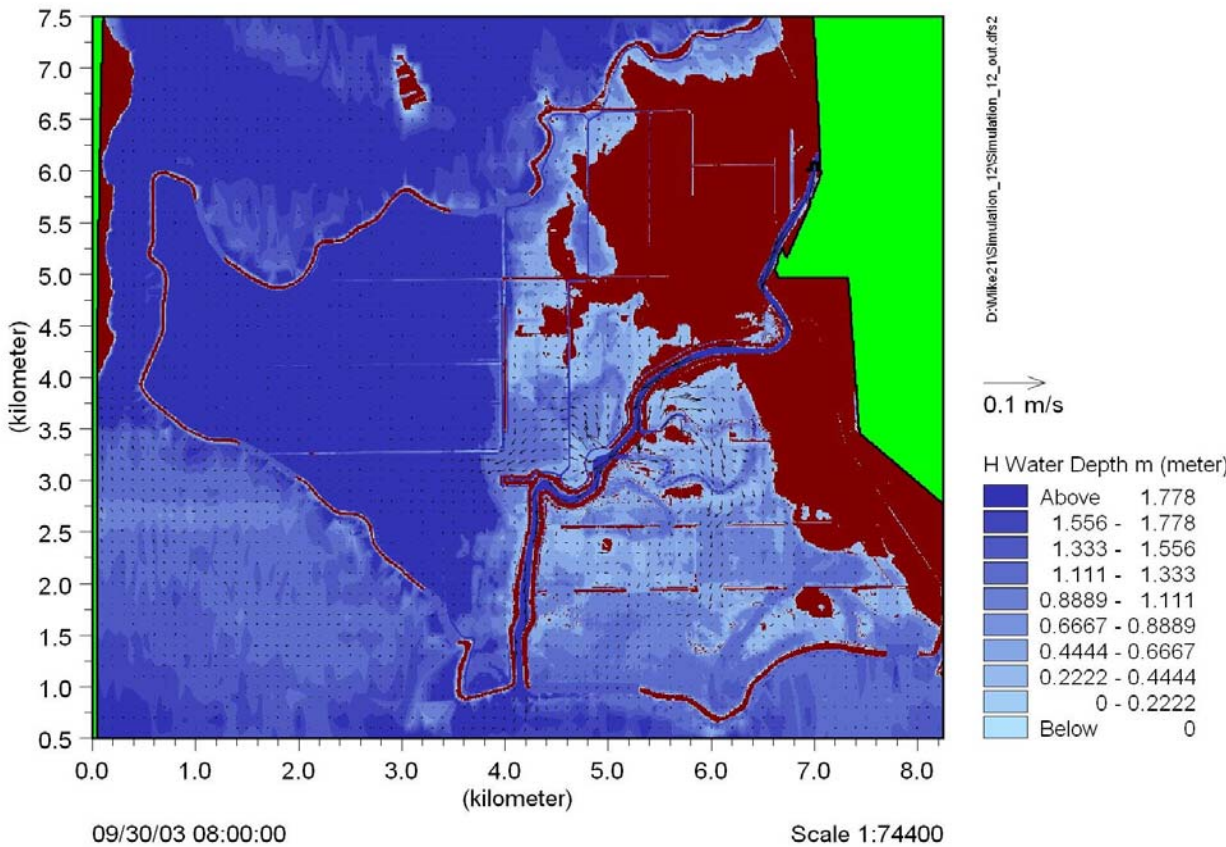

Figure 45. Velocity vector plot showing magnitude (m/s) of the velocity of flow and direction of flow through the study area for the average June hydrologic conditions scenario simulation. Water depth is represented by the background color, dark blue is deeper water than light blue.

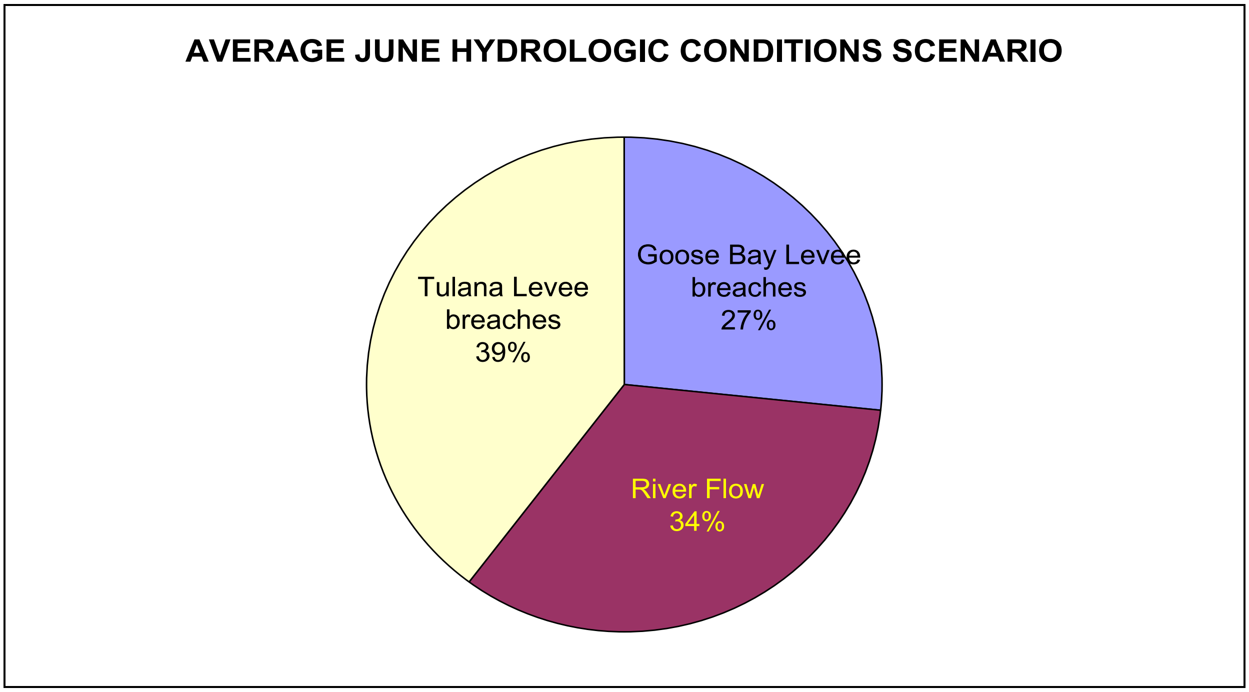

Figure 46. Flow distribution for the reference scenario during median June hydrologic conditions: Percentage of total river flow (847 ft^3/s) through river levee breaches to Tulana and Goose Bay, and the percentage of total flow through the river channel at the mouth of the Williamson River into Upper Klamath Lake.

Table 4 summarizes the percentage of flow through river levee breaches for each of the key model scenarios. It is important to note that the River Mouth Restoration Scenario has a larger simulated levee breach on the Tulana side of the river. This increase in size leads to a greater percentage of flow onto Tulana and lower percentage onto Goose Bay. This scenario was modeled before several refinements were made to the size of levee breaches. The discussion of the results in section 6 takes these minor differences into consideration.

Table 4. Summary of percentage of total river flow through each river levee breach and the river mouth for each of the key model scenarios.

		Percentage of Total River Flow through Levee Breach and River		
Model Scenario	***Total River Flow (ft^3/s)***	***Goose Bay Levee breaches***	***Tulana Levee breaches***	***River Flow***
Reference Scenario	2,070	44%	39%	17%
River Mouth Restoration	2,070	36%	46%	18%
Reference Scenario; No Connection to Agency Lake	2,070	45%	38%	17%
Oxbow Channel Restoration Scenario 1	2,070	53%	38%	9%
Oxbow Channel Restoration Scenario 2	2,070	48%	36%	16%
Narrowed Channel	2,070	45%	41%	14%
100-year Flood; Low Lake	16,000	21%	33%	46%
Average June Hydrologic Conditions	847	27%	39%	34%

5.5 Modeled Alternatives

TNC used the model results presented in sections 5.4.1 through 5.4.7 to develop restoration alternatives for the draft Environmental Impact Statement. In addition to the reference scenario (section 5.4.1), two additional alternatives were simulated for this study and include the preferred alternative and the maximum alternative. These alternatives include some additional river, interior, and shoreline levee breaches, excavation of a historic delta channel near the river mouth, and some adjustments to the river levee breach locations on the Tulana side of the river.

5.5.1 Preferred Alternative

The preferred alternative includes levee breaches as shown in figure 47. The location of levee breaches are the same as in the reference scenario, but with the following changes: There is an additional river levee breach on the Goose Bay side close to the river mouth, the Tulana river levee breach has been moved upstream to a location across from the oxbow channel, and there is an additional river levee breach on the Tulana side downstream of the oxbow. There is an additional shoreline levee breach along Goose Bay between the river and east side of the property, and three additional interior levee breaches in Tulana. Two of these interior levee breaches are along the primary north-south levee and a smaller breach along the northernmost east-west levee. In addition to these new breaches, the Goose Bay oxbow would be dredged to approximately elevation 4136 feet to allow for a continuous, year-round flow connection with the river channel. An alternate delta channel would be excavated to approximately elevation 4136 feet near the river mouth. The model boundary conditions for the preferred alternative are the same as in the reference scenario with a Williamson River discharge of 2,070 ft^3/s, lake water surface elevation of 4143 feet, and discharge from Agency Lake of 745 ft^3/s.

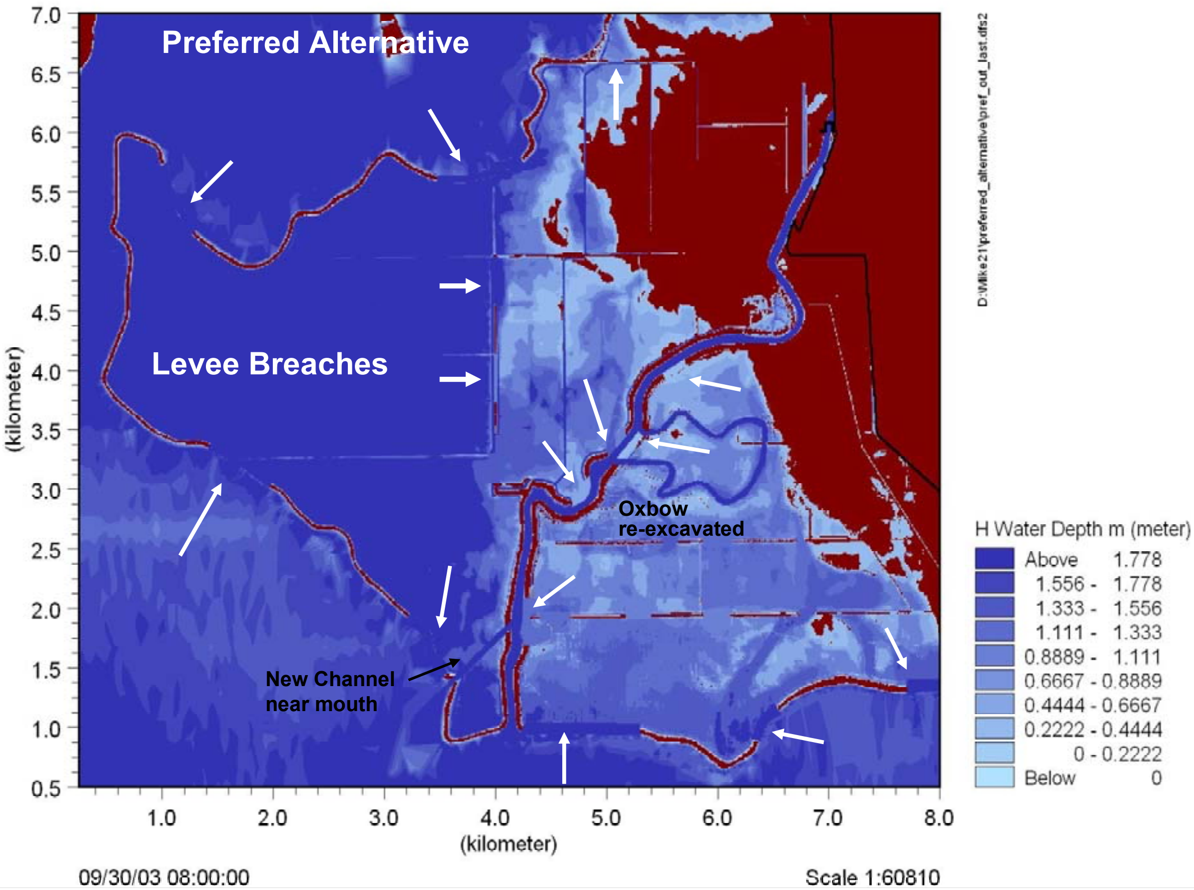

Figure 47. Levee breach locations for the preferred alternative. (Note: The arrows indicate the locations of the levee breaches. In addition, there is a southern most breach of the Tulana interior levee.)

Figure 48 shows the velocity vector plot of the model results for the preferred alternative. Vector lengths represent the magnitude of the flow velocity and the direction of flow. Figure 49 show the percentage of flow through the river levee breaches. Table 5 shows the distribution of flow through river levee sections as a percentage of total river flow (2,070 ft^3/s) and the distribution of flow through each interior levee in Tulana as a percentage of the total flow through all interior levees in Tulana.

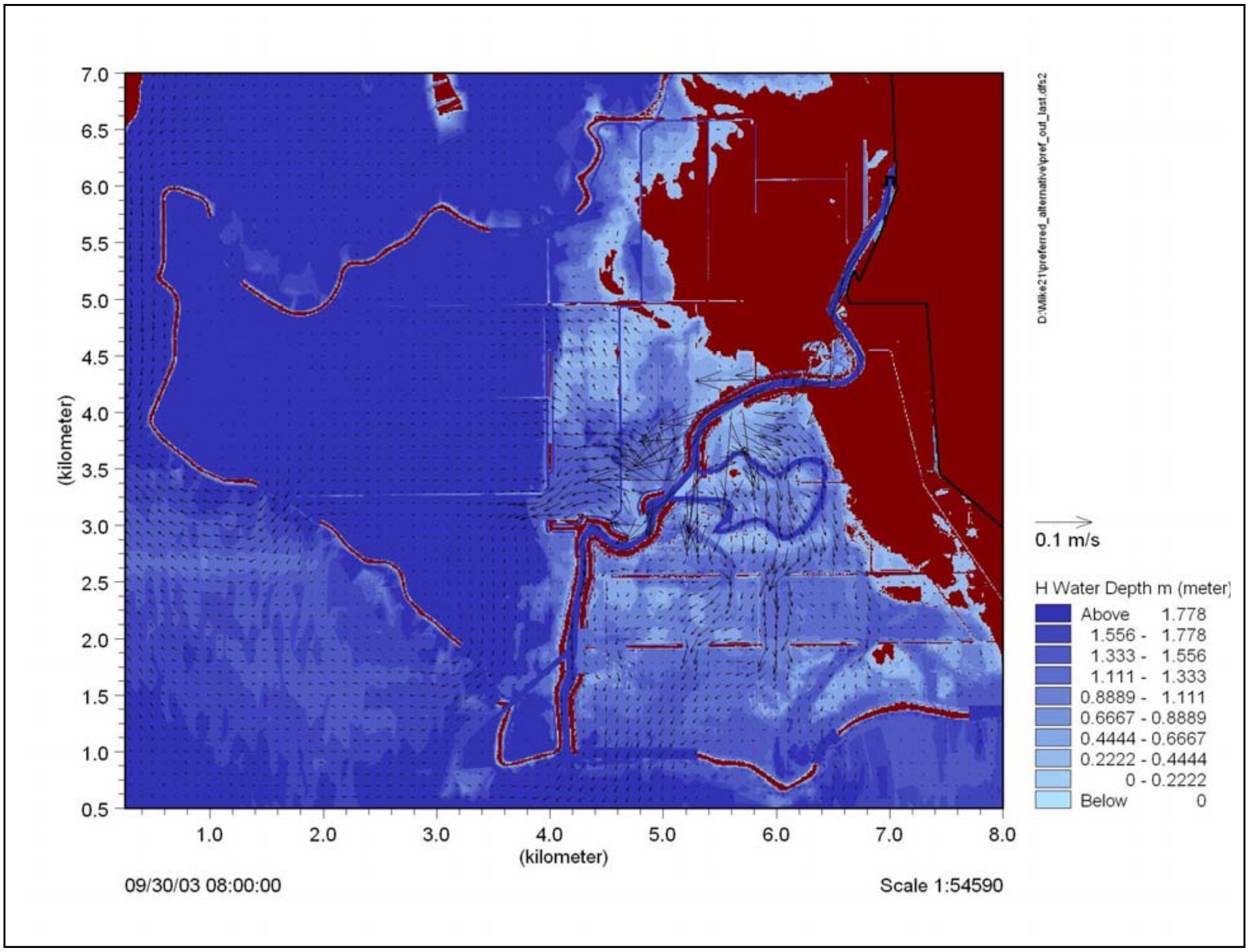

Figure 48. Velocity vector plot for the preferred alternative showing magnitude (m/s) of the flow velocity and direction of flow through the study area. Water depths are represented by the background color, dark blue is deeper water than light blue.

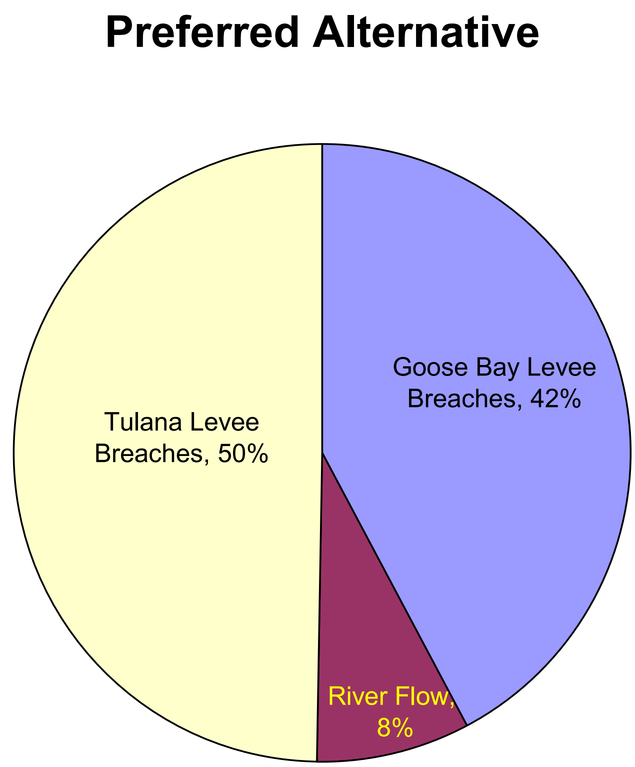

Figure 49. Flow distribution for the preferred alternative: Percentage of total river flow (2,070 ft^3/s) through river levee breaches to Tulana and Goose Bay and the percentage of total river flow through the river channel at the mouth of the river into Upper Klamath Lake.

Table 5. Percentage of flow through river levee breaches, relative to the total river flow (2,070 ft^3/s), and percentage of flow through each interior levee breach in Tulana, relative to the total flow through all interior levees in Tulana.

River Levee Breaches	
Goose Bay	**Percent of Total River Flow**
Upper	18%
Oxbow	22%
Lower	2%
Tulana	
Oxbow	37%
Downstream of Oxbow	11%
New Channel	1%
Interior Breaches	
Tulana	**Percent of Flow Through Each Interior Levee Breach**
South	12%
Middle	42%
North	44%
near Agency Lake	2%

5.5.2 Maximum Alternative

The location of levee breaches under the maximum alternative is the same as in the preferred alternative with the following differences (see figure 50): There is an additional shoreline breach near the river mouth along Upper Klamath Lake on the Tulana side, and the entire north-south running interior levee in Tulana is breached. This alternative also includes filling in the existing river channel between the entrance and exit to the oxbow channel and narrowing the existing river channel by 1/4 to 1/3, beginning downstream of the oxbow and extending to the river mouth. The model boundary conditions for the maximum alternative are the same as in the reference scenario and preferred alternative with a Williamson River discharge of 2,070 ft^3/s, lake water surface elevation of 4143 feet, and discharge from Agency Lake of 745 ft^3/s.

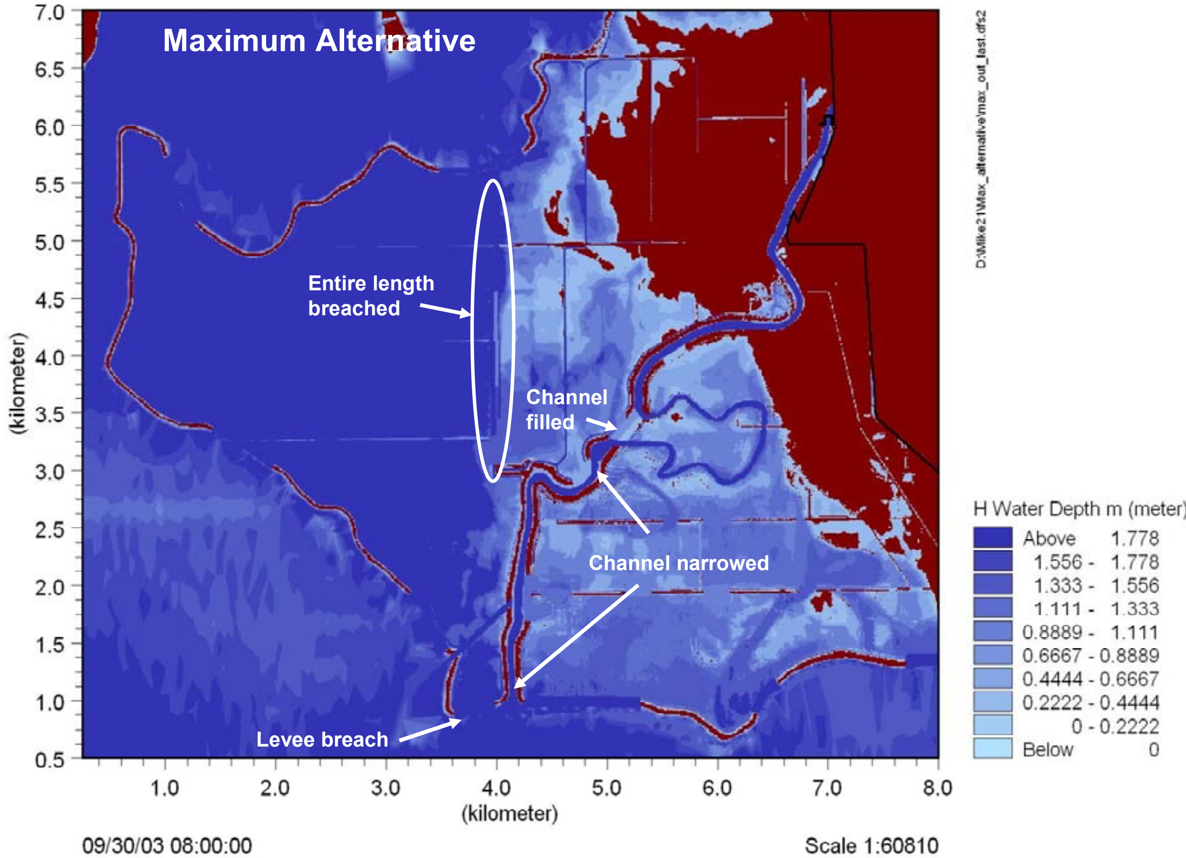

Figure 50. Location of additional levee breaches for the maximum alternative. The remaining levee breaches and channel alterations are the same as in the preferred alternative with the noted differences.

Figure 51 shows the vector plot of the model results for the maximum alternative. Vector length represents the magnitude of the flow velocity and the direction of flow. Figure 52 show the percentage of flow through the river levee breaches. Table 6 shows the distribution of flow through river levee sections as a percentage of total river flow (2,070 ft^3/s). Because the river channel would be filled in between the entrance and exit to the oxbow channel, more flow would get overbank onto Tulana and Goose Bay than would in the preferred alternative.

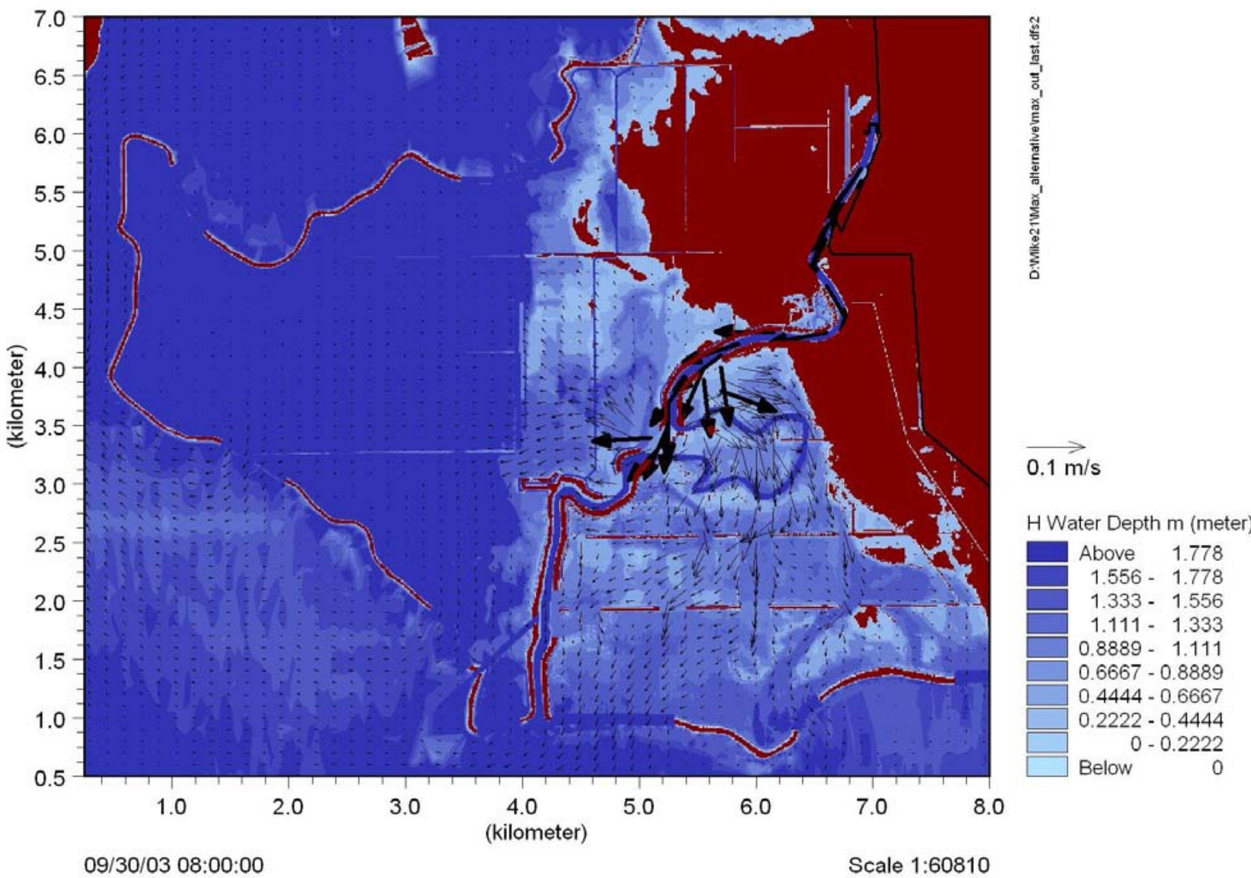

Figure 51. Velocity vector plot for the maximum alternative showing magnitude (m/s) of the velocity of flow and direction of flow through the study area. Water depth is represented by the background color, dark blue is deeper water than light blue.

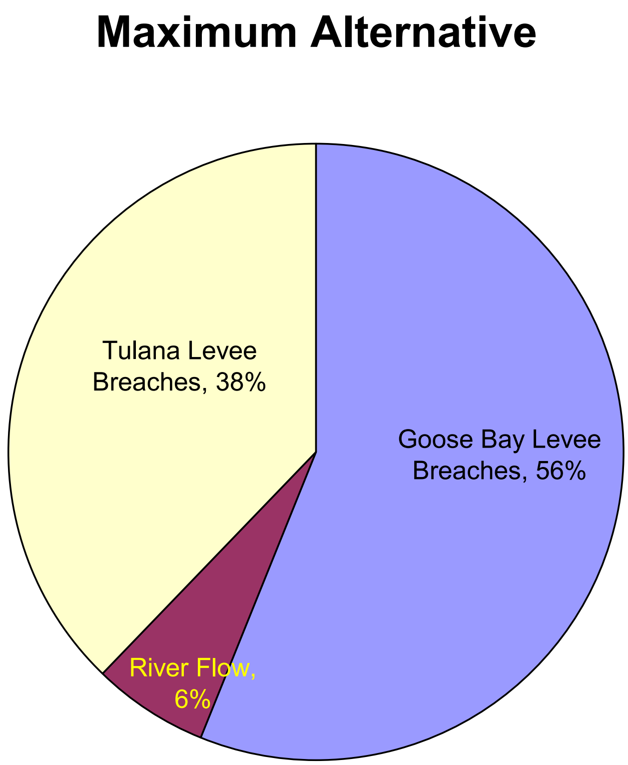

Figure 52. Flow distribution for the maximum alternative: Percentage of total river flow (2,070 ft3/s) through river levee breaches to Tulana and Goose Bay and the percentage of total river flow through the river channel at the mouth of the river into Upper Klamath Lake.

Table 6. Percentage of flow through river levees as a percentage of total river flow (2,070 ft^3/s).

Section	
River Levee Breaches	
Goose Bay	**Percent of Total River Flow**
Upper	26%
Oxbow	33%
Lower	-3%
Tulana	
Oxbow	30%
Middle	7%
New Channel	1%

5.6 Effects of Scenarios on Flood Stage

Figure 53 shows a longitudinal profile of the water surface elevation for select scenarios beginning at the river mouth (river mile 0) and moving upstream. The oxbow area is located between river miles 2.5 and 2.2 on the graph. Under existing conditions with the river completely confined within its levees, the water surface profile for the 1.5 year flood, along with a lake water surface elevation of 4143 feet, is very flat (the scale in figure 53 greatly exaggerates the rise in water surface elevation). The water surface elevation under existing conditions upstream from river mile 4.5 is only 1.8 inches higher than the lake water surface elevation. For all modeled scenarios, the presence of levee breaches causes a decline in the upstream water surface elevation. Water surface elevations around river mile 4.5 for all levee breach scenarios rise just over 1 inch from the lake water surface elevation. Levee breaches cause a slight decline in upstream water surface elevations during the 1.5 year flood and high lake conditions.

Figure 54 shows a longitudinal profile of the water surface for the same scenarios for the 100-year flood (16,000 ft^3/s) with a low lake elevation of 4140 feet. Under existing conditions, with river flow contained within levees, the water surface approximately 4.5 river miles upstream is 7 feet higher than the lake water surface elevation. For all the modeled scenarios, the water surface elevation is higher than the lake surface elevation, but lower throughout the reach than the existing condition. Levee breaches cause a decrease in flood stage, at river mile 4.5, of 1.5 feet for the 100-year flood.

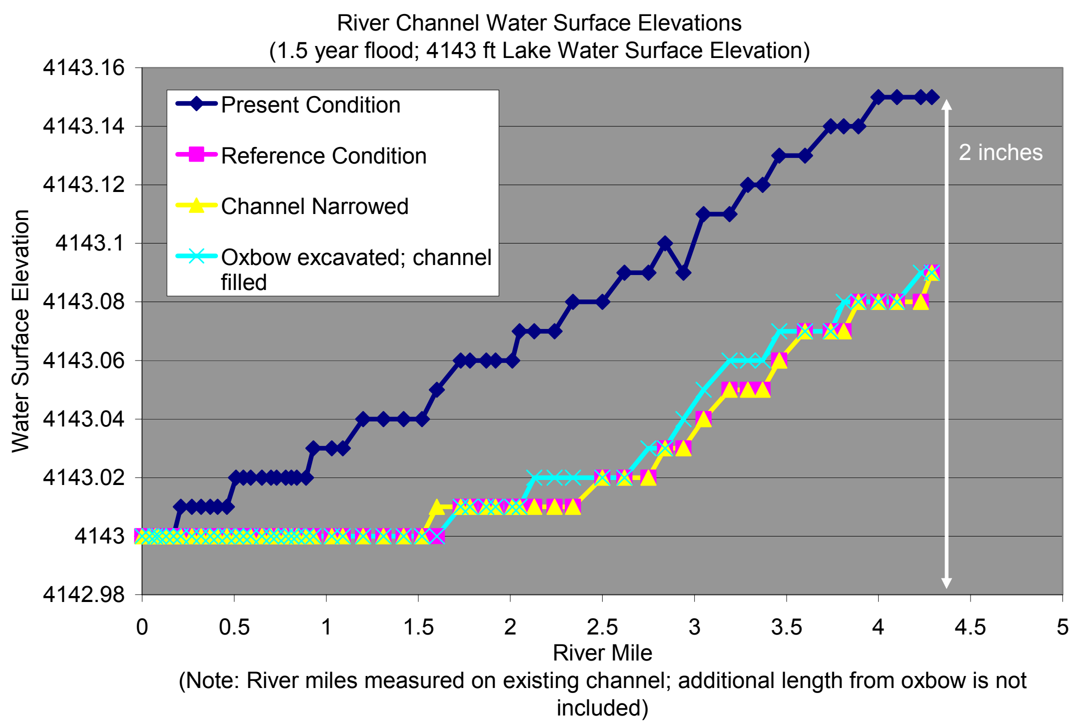

Figure 53. Water surface profiles for the 1.5 year flood of the Williamson River under several different modeled scenarios. Note that the scale for elevation is only 2 inches, while the scale for river miles is 5 miles.

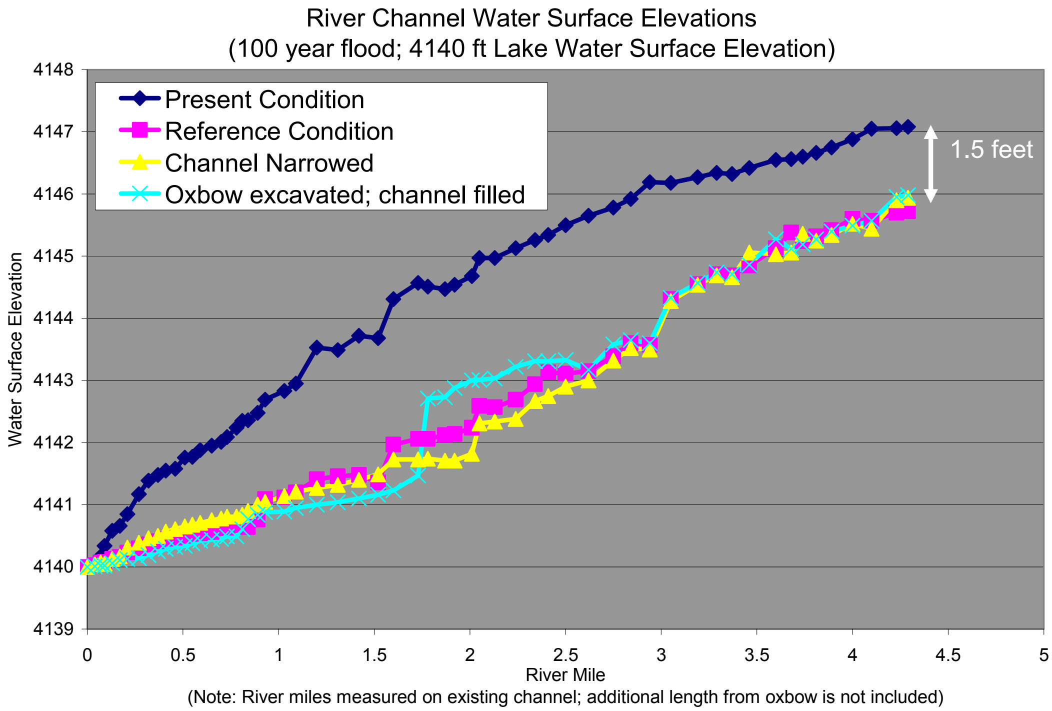

Figure 54. Water surface profiles for the 100-year flood of the Williamson River under several different modeled scenarios. Note that the scale for elevation is 9 feet, while the scale for river miles is 5 miles.

5.7 Volume of Levee Material Removal

The length, width, and volume of each simulated river, shoreline, and interior breach, as specified in the reference scenario, are given in tables 7, 8, and 9. The estimated volumes of material needed for river channel modifications are listed in tables 8 and 9. The river channel modifications include re-excavating the oxbow channel, re-excavating a new delta channel, and narrowing the main river channel by one third, downstream from the levee breaches.

Table 7. Estimates of the levee breach volumes for the reference scenario.

Reference Scenario Levee Breach Volume Estimate							
Levee Breach Locations	Breach Length (ft)	Breach bottom width (ft)	Breach Top width (ft)	Breach Height (ft)	Breach volume (yd^3)	Breach top elevation (ft)	Breach bottom elevation (ft)
River Breaches							
Upper Goose Bay	787	131	33	6.9	16,480	4149.0	4142.1
Middle Goose Bay at oxbow	1,312	131	33	12.4	49,244	4152.9	4140.5
Tulana	1,280	131	33	7.4	28,884	4148.0	4140.5
Shoreline Breaches							
Goose Bay west	3,510	197	33	10.0	148,908	4148.0	4138.0
Goose Bay east	1,017	262	33	10.0	55,468	4148.0	4138.0
Tulana Upper Klamath Lake west	2,133	197	33	7.3	66,653	4145.3	4138.0
Tulana Upper Klamath Lake east	2,067	197	33	10.0	87,675	4148.0	4138.0
Tulana Agency Lake west	2,156	197	33	8.0	73,386	4146.0	4138.0
Tulana Agency Lake east	2,667	197	33	9.0	101,977	4147.0	4138.0
Interior Breaches							
Goose Bay[2]							
northern east-west 1	456	79	33	5.0	4,667	4146.0	4141.0
northern east-west 2	453	79	33	7.0	6,505	4146.0	4139.0
northern east-west 3	856	79	33	6.0	10,562	4145.0	4139.0
northern east-west 4	253	79	33	5.9	3,099	4146.0	4140.1
southern east-west 1	899	79	33	6.0	11,088	4145.0	4139.0
southern east-west 2	761	79	33	6.0	9,389	4145.0	4139.0
southern east-west 3	820	79	33	6.0	10,117	4145.0	4139.0
southern east-west 4	509	79	33	4.7	4,894	4143.7	4139.0
Tulana							
north-south 1 (south end)	1,362	98	16	6.0	17,288	4144.0	4138.1
Total Levee Breach Volume					706,000		
Uncertainty (+15%)					106,000		
Grand Total Levee Breach Volume					**812,000**		

[2]Interior breaches are numbered from west to east in Goose Bay (see figure 10)

Table 8. Levee breach volume estimates for the preferred alternative. Estimates of the volume of material excavated from the oxbow channel are also given.

Preferred Alternative Levee Breach Volume Estimate							
Levee Breach Locations	Breach Length (ft)	Breach bottom width (ft)	Breach Top width (ft)	Breach Height (ft)	Breach volume (yd^3)	Breach top elevation (ft)	Breach bottom elevation (ft)
River Breaches							
Upper Goose Bay	787	131	33	6.9	16,480	4149.0	4142.1
Middle Goose Bay at oxbow	1,312	131	33	12.4	49,244	4152.9	4140.5
Lower Goose Bay	1,312	180	33	10.4	53,816	4150.9	4140.5
Upper Tulana	833	131	33	8.9	22,549	4148.0	4139.1
Lower Tulana	863	131	33	6.9	18,146	4148.0	4141.0
Shoreline Breaches							
Goose Bay west	3,510	230	33	10.0	170,180	4148.0	4138.0
Goose Bay middle	1,112	262	33	10.0	60,656	4148.0	4138.0
Goose Bay east	1,017	262	33	10.0	55,468	4148.0	4138.0
Tulana Upper Klamath Lake west	2,133	197	33	7.3	66,653	4145.3	4138.0
Tulana Upper Klamath Lake east	2,067	197	33	10.0	87,675	4148.0	4138.0
Tulana Agency Lake west	2,156	197	33	8.0	73,386	4146.0	4138.0
Tulana Agency Lake east	2,667	197	33	9.0	101,977	4147.0	4138.0
Interior Breaches							
Goose Bay[2]							
northern east-west 1	456	79	33	5.0	4,667	4146.0	4141.0
northern east-west 2	453	79	33	7.0	6,505	4146.0	4139.0
northern east-west 3	856	79	33	6.0	10,562	4145.0	4139.0
northern east-west 4	253	79	33	5.9	3,099	4146.0	4140.1
southern east-west 1	899	79	33	6.0	11,088	4145.0	4139.0
southern east-west 2	761	79	33	6.0	9,389	4145.0	4139.0
southern east-west 3	820	79	33	6.0	10,117	4145.0	4139.0
southern east-west 4	509	79	33	4.7	4,894	4143.7	4139.0
Tulana							
north-south 1 (south end)	1,362	98	16	6.0	17,288	4144.0	4138.1
north-south 3	1,348	98	16	5.2	15,052	4145.0	4139.8
north-south 5	1,273	98	16	6.0	16,252	4142.1	4136.1
northern east-west	492	98	16	7.0	7,347	4147.0	4140.0
Channel Modifications							
Oxbow channel excavation	11,667	149	149	2.3	148,219	4138.3	4136.0
New delta mouth channel	2,474	155	155	3.6	50,527	4139.6	4136.0
Total Levee Breach and channel modification Volume					1,090,000		
Uncertainty (+15%)					160,000		
Grand Total Levee Breach and channel excavation Volume					**1,250,000**		

[2]Interior breaches are numbered from west to east in Goose Bay (see figure 10)

Table 9. Levee breach volume estimates for the maximum alternative. Estimates of the volume of fill for the narrowed channel scenario and the volume of material excavated from the oxbow channel are also given.

Maximum Alternative Levee Breach Volume Estimate							
Levee Breach Locations	Breach Length (ft)	Breach bottom width (ft)	Breach Top width (ft)	Breach Height (ft)	Breach volume (yd^3)	Breach top elevation (ft)	Breach bottom elevation (ft)
River Breaches							
Upper Goose Bay	787	131	33	6.9	16,480	4149.0	4142.1
Middle Goose Bay at oxbow	1,312	131	33	12.4	49,244	4152.9	4140.5
Lower Goose Bay	1,312	180	33	10.4	53,816	4150.9	4140.5
Upper Tulana	833	131	33	8.9	22,549	4148.0	4139.1
Lower Tulana	863	131	33	6.9	18,146	4148.0	4141.0
Shoreline Breaches							
Goose Bay west	3,510	230	33	10.0	170,180	4148.0	4138.0
Goose Bay middle	1,112	262	33	10.0	60,656	4148.0	4138.0
Goose Bay east	1,017	262	33	10.0	55,468	4148.0	4138.0
Tulana Upper Klamath Lake west	2,133	197	33	7.3	66,653	4145.3	4138.0
Tulana Upper Klamath Lake east	2,067	197	33	10.0	87,675	4148.0	4138.0
Tulana Upper Klamath Lake mouth	1,230	164	33	10.0	44,732	4148.0	4138.0
Tulana Agency Lake west	2,156	197	33	8.0	73,386	4146.0	4138.0
Tulana Agency Lake east	2,667	197	33	9.0	101,977	4147.0	4138.0
Interior Breaches							
Goose Bay[2]							
northern east-west 1	456	79	33	5.0	4,667	4146.0	4141.0
northern east-west 2	453	79	33	7.0	6,505	4146.0	4139.0
northern east-west 3	856	79	33	6.0	10,562	4145.0	4139.0
northern east-west 4	253	79	33	5.9	3,099	4146.0	4140.1
southern east-west 1	899	79	33	6.0	11,088	4145.0	4139.0
southern east-west 2	761	79	33	6.0	9,389	4145.0	4139.0
southern east-west 3	820	79	33	6.0	10,117	4145.0	4139.0
southern east-west 4	509	79	33	4.7	4,894	4143.7	4139.0
Tulana							
north-south 1 (south end)	1,362	98	16	6.0	17,288	4144.0	4138.1
north-south 2	883	98	16	6.0	11,206	4144.0	4138.1
north-south 3	1,348	98	16	9.0	25,682	4145.0	4136.1
north-south 4	1,375	98	16	8.0	23,305	4144.0	4136.1
north-south 5	1,273	98	16	6.0	16,252	4142.1	4136.1
north-south 6 (north end)	1,946	98	16	4.0	16,559	4140.1	4136.1
northern east-west	492	98	16	7.0	7,347	4147.0	4140.0
Channel Modifications							
Oxbow channel excavation	11,667	149	149	2.3	148,219	4138.3	4136.0
New delta mouth channel	11,667	149	149	2.3	148,219	4138.3	4136.0
Lower river channel narrowing	9,724	65	65	12.5	291,939		
Total Levee Breach and channel modification Volume					1,590,000		
Uncertainty (+15%)					240,000		
Grand Total Levee Breach and channel excavation Volume					**1,830,000**		

[2]Interior breaches are numbered from west to east in Goose Bay (see figure 10)

6.0 Discussion

6.1 Application and Comparison of Model Scenarios and Alternatives

The results of the base condition, summarized in section 5.2, provide a guideline for the location of all levee breaches. The dominant areas where flow overtopped the river banks in the absence of levees determined where levee breaches were located in the reference scenario. Additionally, the dominant flow paths shown in the base condition were the primary determinants in locating interior and lake shoreline levee breaches in the reference scenario.

6.1.1 Reference Scenario

The reference scenario serves as a foundation upon which the design and location of levee breaches may be based. All model scenarios discussed below may be seen as modifications of the reference scenario.

As shown by the velocity vector plot (figure 21, section 5.4.1), the flow patterns across the floodplain/delta on both sides of the river, Tulana and Goose Bay, for the reference scenario are very similar to the flow patterns observed for the base condition (figure 15). This indicates that the locations of river, interior, and shoreline levee breaches are satisfactory to re-establish an efficient hydraulic connection between the river and the floodplain. The quantity of flow through each breach is dependent on the size of each levee breach, and there is an interaction between upstream and downstream breaches as well.

6.1.2 River Mouth Restoration

There is no change in the quantity of overbank flow through levee breaches in the upstream river reaches with additional levee breaches near the river mouth. The location of these downstream breaches is in a lake backwater area where there is no slope to the water surface, around river mile 0.5 (see figure 54). That is, alterations to the river and levee breaches in the vicinity of the river mouth have no effect on the hydraulics upstream. Additionally, flow patterns in Goose Bay and Tulana are relatively unaffected by levee breaches near the river mouth. However, levee breaches near the river mouth would serve to restore the river to its alignment observed in the 1940-41 photo, and would allow the hydraulics of flow to better match the flow observed on the base condition. Restoration of the river mouth does not have an effect on restoration of the hydraulic connection of the river with Tulana and Goose Bay.

6.1.3 Reference Scenario without connection to Agency Lake

Since there is no observed difference in the hydraulics of flow in Tulana with shoreline levees breached or not breached along Agency Lake for the 1.5 year flood, decisions regarding levee breaches in this area can be made on other grounds, such as water quality and cost. The effects of wind on flow patterns and the hydraulics of flow during high flow events in the Wood River and Seven Mile River could effect hydraulics of flow in Tulana. Additionally, water quality issues may be more important.

6.1.4 Oxbow Channel Restoration

Under the oxbow channel restoration scenario 2, which does not include filling of the main channel, the flow patterns across the floodplain/delta on both sides of the river are similar to those observed for the reference condition. There is not a significant change in the amount of flow through the levee breaches when compared to the reference scenario. However, a greater quantity of flow gets out in the oxbow reach on the Goose Bay side as a result of the re-excavation of the oxbow channel. This also leads to a slight decrease in the relative amount of flow getting out into the Tulana side. The changes in quantity of flow do not alter the flow patterns. The reason that greater changes in flow quantities and patterns are not observed is because the simulation was done at a high lake level. Since the area is fully inundated, the depth averaged flow and velocity does not change significantly. Greater changes in flow patterns in the oxbow area are expected at lower lake elevations.

Reconnection of historic oxbow channel represents the most efficient way to restore a significant portion of the historic river channel alignment and connection of the river with the floodplain/delta. At low lake level, there can be a continuous surface water connection with the oxbow with levee removal to proper elevations with or without re-excavation of the historic oxbow channel.

Figure 55 shows an inundation map of the floodplain/delta. The dark blue shows the land area that is inundated at a water surface elevation of 4140 feet, and the translucent blue shows the land surface that is inundated at a water surface elevation of 4143 feet. The majority of the floodplain/delta, both the Tulana and Goose Bay, is inundated when the lake level reaches 4143 feet.

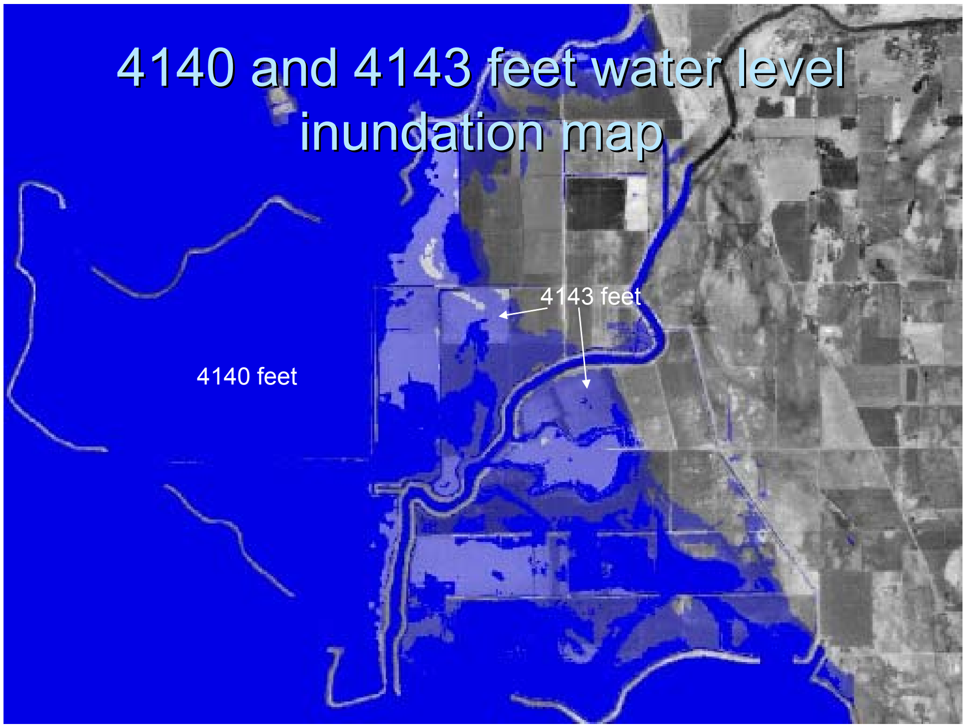

Figure 55. Inundation map of the floodplain/delta. Dark blue shows area of inundation with a lake water surface elevation of 4140 feet and the translucent blue shows the area of inundation with a lake water surface elevation of 4143 feet.

Figure 56 shows a zoomed in view of the oxbow channel with inundation levels of 4140 and 4143 feet. When the lake surface is at 4143 feet, the entire oxbow and the surrounding floodplain/delta is inundated. When the lake surface is at 4140 feet, the floodplain/delta surrounding the oxbow is no longer inundated, but much of the existing remnants of the oxbow would be inundated. Additionally, a connection with the main channel would be maintained if levees were breached down to elevation 4136 feet, as is shown in figure 56. Figure 57 shows the inundated area if the lake water surface elevation was 4138 feet including breaching levees to an elevation of 4136 feet at the entrance and exit of the oxbow channel.

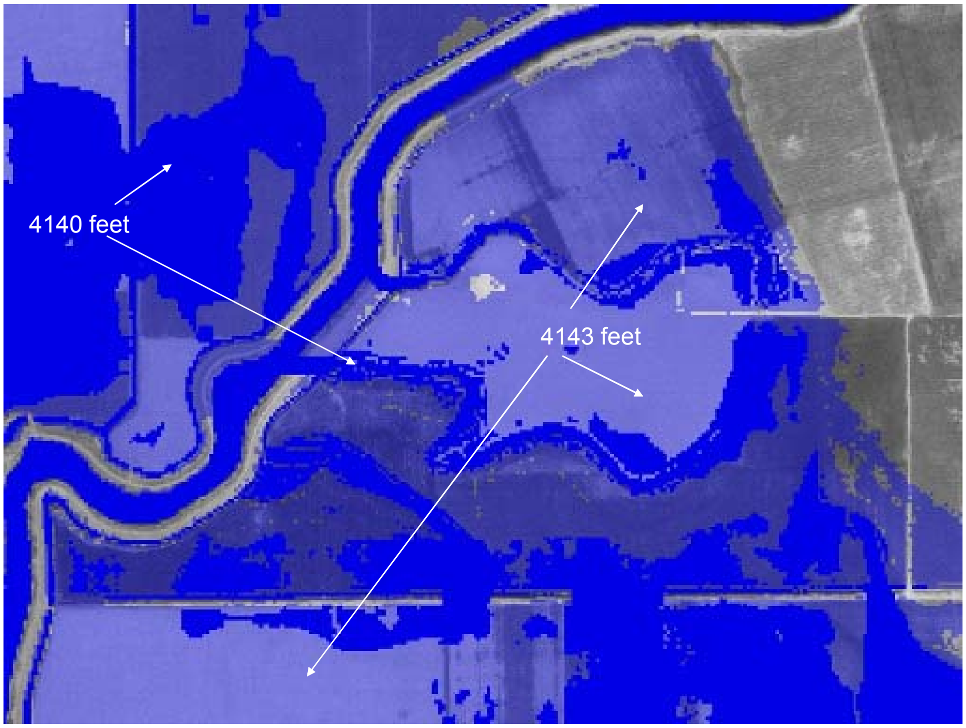

Figure 56. Zoomed in view of the Oxbow Channel. Dark blue shows area of inundation with a lake water surface elevation of 4140 feet and the translucent blue shows the area of inundation with a lake water surface elevation of 4143 feet. Inundation is shown with the simulated removal of levees.

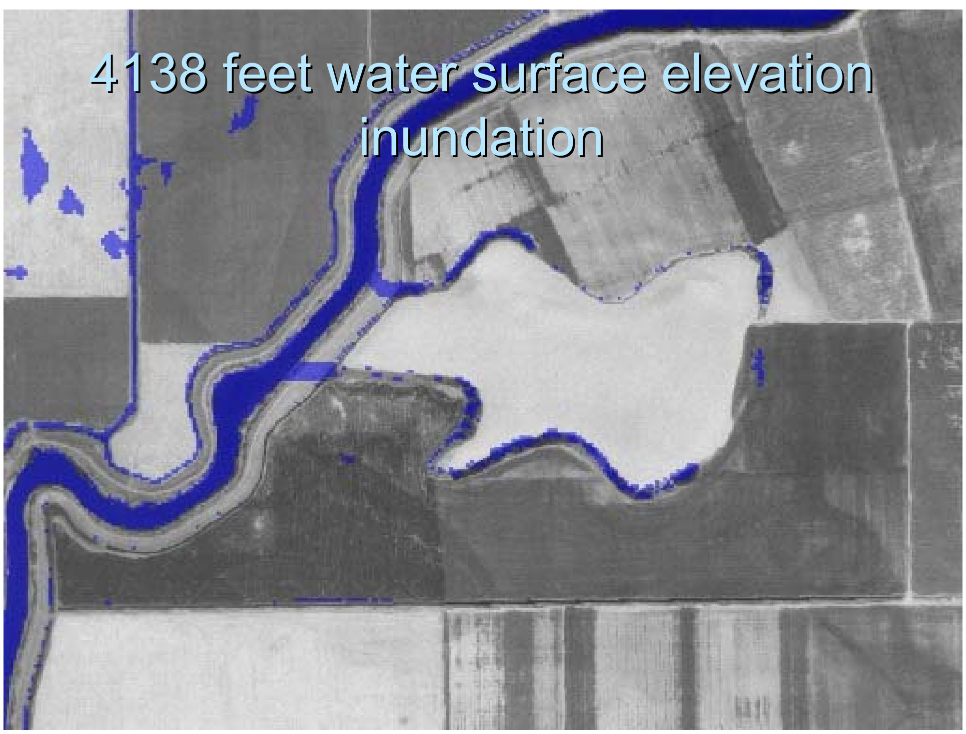

Figure 57. Inundation map of the oxbow channel. Blue shows area of inundation with a lake water surface elevation of 4138 feet. Inundation is shown with the simulated removal of levees including breaching to an elevation 4136 feet at the entrance and exit to the oxbow channel.

It is apparent from figures 56 and 57 that if river levees are breached, there would be an almost continuous connection under existing conditions of the existing oxbow remnant and the main channel when lake water surface elevations were greater than 4138 feet. There are several areas where the land surface is too high and an area where a levee or road blocks the continuous connection. In order to create a continuous connection and re-establish the oxbow channel, the channel would need to be excavated to an approximate elevation of 4136 feet. This would insure that the oxbow was continuously connected to the main channel, at all lake water surface elevations, and that the connection allowed flow through the entire length of the oxbow channel from the entrance to the exit. Excavation of the oxbow channel in scenario 2 does not entail filling of the main channel, as it does in scenario 1. Restoration of the oxbow channel can be carried out without filling main channel and, thus, without affecting navigation in the river. It is suggested that excavation of the oxbow channel be done in such a manner so that there is some downstream slope from the entrance to the exit. This would create a channel bottom slope to the oxbow that would facilitate directional flow in the channel.

6.1.5 Narrowed Channel

Since the simulated channel narrowing is downstream from the three proposed levee breaches, there is little effect on water surface elevations. Because of this, there is also only a slight increase in the amount of flow crossing through each of the levee breaches. Overall, the flow rate reaching the river mouth decreases from 17 to 14 percent of the 1.5-year flood. This leads to only a two percentage point increase in the relative flow into Tulana and a one percentage point increase in the relative amount of flow reaching Goose Bay. In other words, the amount of flow and flow patterns across Tulana and Goose Bay are not significantly different than that observed for the reference scenario.

As shown in figure 54, the water surface elevation under this scenario is lower than the water surface elevation under existing conditions at all points along the river, even when the river flow rate is equivalent to the 100-year flood (16,000 ft^3/s). This shows that the presence of levee breaches will lead to a reduction in upstream flood stage that will offset the effects of any modest channel alterations downstream of levee breaches. The results indicate that narrowing the channel downstream of the oxbow by 1/4 to 1/3, with the presence of levee breaches, does not increase the upstream flood stage compared to existing conditions.

6.1.6 100-year Flood

The 100-year flood is estimated to be 16,000 ft^3/s. This flow rate represents almost 8 times the flow rate of the 1.5 year flood, therefore significant increases in the amount of overbank flow into both Goose Bay and Tulana are observed in this simulation. The relative amount of flow out of each levee breach is also different for the 100-year flood compared with the reference scenario (compare figures 23 and 43). Regardless of this difference, there is still a large amount of flow onto the floodplain/delta during the 100-year flood event. Additionally, patterns of flow across the floodplain/delta are similar to the reference scenario. Velocities across the floodplain are 2 to

3 times greater under this scenario as compared to the reference scenario, but this is also expected given the large increase in flow rate.

It should be noted that under this scenario, a low lake elevation of 4140 feet was used. Under these conditions, flow gets out of bank at all river levee breaches and flows onto the floodplain/delta at a time when the floodplain/delta is not completely inundated by the lake. Additionally, since the lake is low, the upstream flood stage would be at its lowest elevation during this flow rate. There is a possibility that lake water surface elevations could be slightly higher during an event of this magnitude, up to 4142 feet. The relative amount of flow through levees may be slightly altered in this case, however little or no change in the flow patterns through Tulana or Goose Bay is expected.

The highest flood stage would occur in the upstream river channel if the 100-year flood occurred when the lake water surface elevation was at its highest, 4143 feet. Figure 58 shows that water surface elevations would be lower with river levee breaches present—as under the reference scenario—than they are under existing conditions. As was shown in section 5.5, water surface elevations under all key model scenarios are lower than water surface elevations under existing conditions. Therefore, if a 100-year flood event occurred when the lake was high, the levee breaches would result in a lower flood stage than would occur under existing conditions.

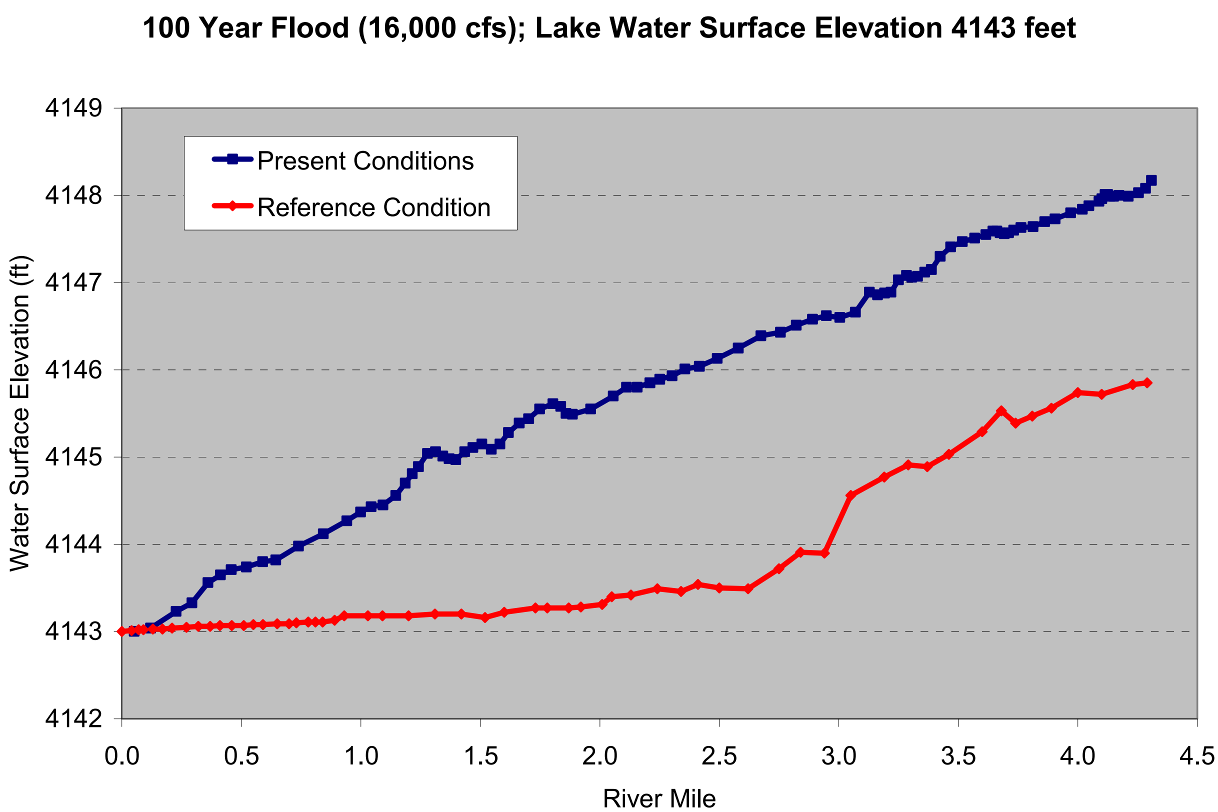

Figure 58. Water Surface Elevations computed in HEC-RAS for the 100-year flood (16,000 ft^3/s) and a high lake surface elevation (4143 feet). Dark blue line shows the water surface elevation under existing conditions and the red line shows the water surface elevations under the reference scenario.

6.1.7 Average June Hydrologic Conditions

The most significant difference between this scenario and the reference scenario is that flow does not get out of bank at the upper river levee breach onto Goose Bay. Flow does get out of bank through the levee breaches at the oxbow reach on both sides of the river, and once on the floodplain/delta, flow patterns are similar to those observed in the reference scenario in Tulana and south of the oxbow in Goose Bay. Because flow does not get out of bank at the upper levee breach, flow through the oxbow breach onto Goose Bay tends to flow northeast over the floodplain/delta (see figure 45) towards the upper breach.

The flow patterns in the oxbow region of the floodplain/delta at this flow rate and lake elevation can be much improved by re-excavation of the oxbow channel. Flow would be less restricted by high points in elevation and would be facilitated by the presence of a channel.

6.1.8 Late Summer Hydrologic Conditions for the Preferred Alternative

The preferred alternative (see section 5.5.1) was simulated with hydrologic conditions that are likely to occur in the late summer when river flow and lake water surface elevations are typically low. For this simulation, the lake water surface elevation was set to 4140 feet and the Williamson River flow was set to 520 ft^3/s. This simulation was done to establish that there would be a viable flow through the re-excavated oxbow channel from its upstream connection to the main channel to the downstream connection at times of low flow and low lake water surface elevation. Figure 59 shows a vector plot of the entire study area for the preferred alternative at low flow and low lake elevation. It is important to note that the changes and additions in levee breach locations do not affect the flow rate in the oxbow channel. Figure 60 shows a vector plot zoomed into the oxbow region.

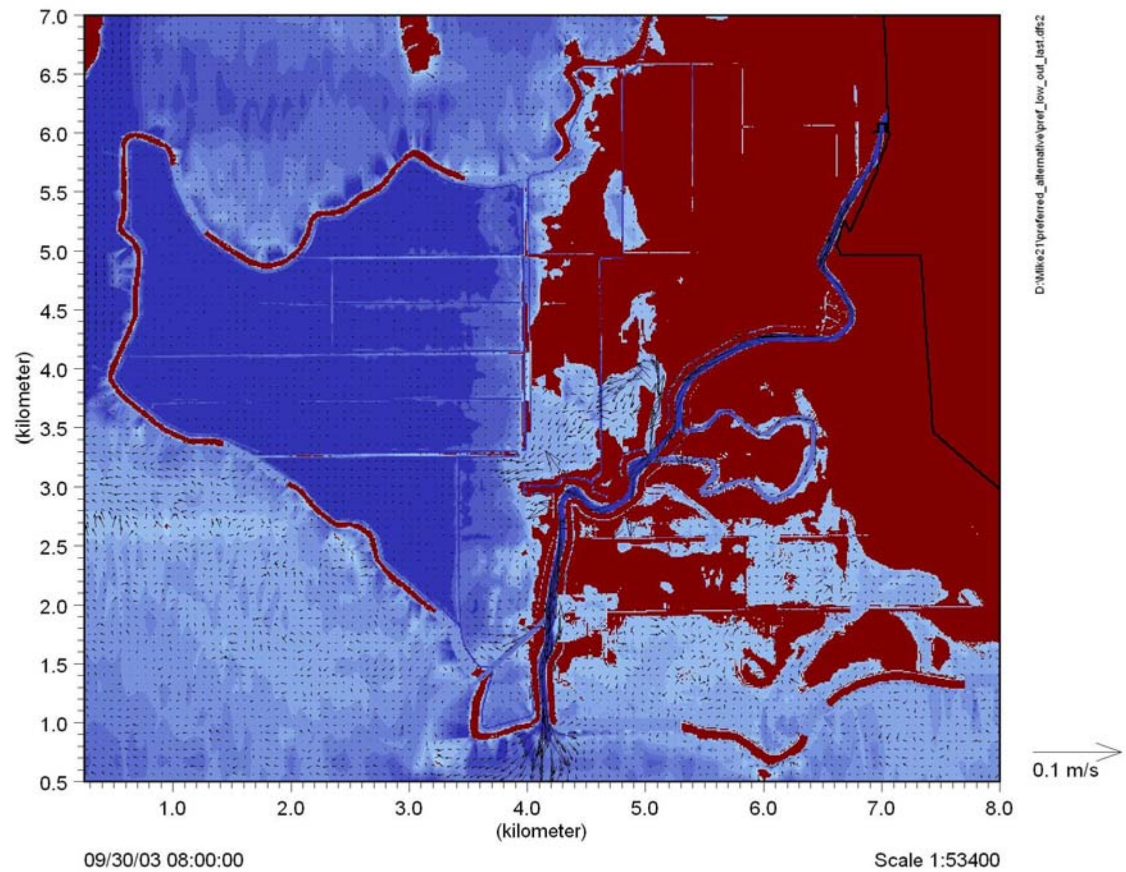

Figure 59. Velocity vector plot of the preferred alternative showing magnitude (m/s) of the velocity of flow and direction of flow through the study area for a low flow (520 ft^3/s) and low lake (4140 feet). Water depth is represented by the background color, dark blue is deeper water than light blue.

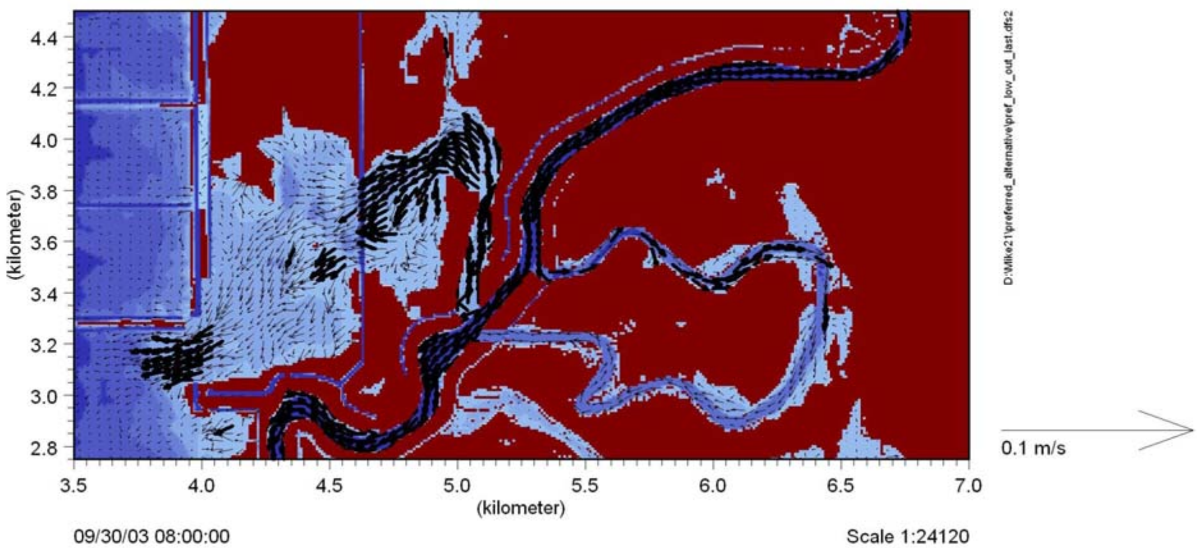

Figure 60. Velocity vector plot of the preferred alternative showing magnitude (m/s) of the velocity of flow and direction of flow through the oxbow region of the study area for a low flow (520 ft^3/s) and low lake (4140 feet). Water depth is represented by the background color, dark blue is deeper water than light blue.

Figure 60 shows that, with a river flow of 520 ft^3/s and a lake elevation of 4140 feet, there is good circulation through the re-excavated oxbow channel. Flow through the oxbow is approximately 4% of the total river flow. The flow velocity through the oxbow channel is about ½ inch per second. This is a slow flow, but there is flow nonetheless. It is interesting to note that the natural topography of the floodplain/delta on the Tulana side of the river allows for a hydraulic connection between the main channel and the floodplain/delta at this low flow and lake water surface elevation. The flow into Tulana is about 11% of the total river flow and the depths of flow range from 1 to 2 feet in this flow area. Beaching the levee on the Tulana side of the river, across from the exit to the oxbow, down to an elevation matching that of the surrounding floodplain/delta (4138 feet) would allow for a continuous hydraulic connection during most years.

6.1.9 Preferred Alternative

The preferred alternative is similar to the reference scenario, but has many added features that more closely match the natural flow patterns for the case without any levees. The additional levee breaches near the mouth and the re-excavation of the historic delta channel would allow flow to take a more natural course. Re-excavation of the oxbow channel would restore a significant channel across the floodplain/delta area of Goose Bay. The additional shoreline levee breach would help avoid a flow stagnation point in Goose Bay. The additional interior levee breaches in Tulana would help with flow circulation to the west and north from the river levee breach.

6.1.10 Maximum Alternative

The maximum alternative incorporates the maximum extent of levee breaches and the maximum extent of all river channel modifications from all modeled scenarios. This alternative represents the maximum extent of impacts that would be considered as part of the draft Environmental Impact Statement.

6.2 Potential Effects on Fish Migration

An important aspect of the restoration project is the hydraulic connection between the river and the floodplain/delta because fish would depend on this connection for their migration and use of the new habitat area. The flow velocity through a potential levee breach, relative to the flow velocity through the river channel, is an important parameter for fish. The flow velocity through the levee breach needs to be high enough so that fish will be carried from the river onto the floodplain/delta. Figure 61 is a zoomed in view of the upstream river breach onto Goose Bay showing the velocity vectors and water depth in this area. Figure 62 is a zoomed in view of the river levee breaches in the oxbow reach of the river and flow onto Goose Bay and Tulana. The velocity of overbank flow from the river onto the floodplain is of a similar magnitude to the velocity of flow within the river channel in both levee breach areas. This is an indication that the hydraulics of the flow is sufficient to allow fish migration onto the floodplain/delta. Other factors that may be required for fish migration are not considered here.

Velocity vector plots of the upper river breach onto Goose Bay for each of the other scenarios considered—where water flows overbank through this breach—shows the same result in terms of the magnitude of the velocity of flow overbank. Velocity of flow overbank at this breach is of a similar magnitude to velocity of flow in the channel for all model scenarios.

Velocity vector plots of the river levee breaches in the oxbow reach show similar results in all model scenarios with the exception of the oxbow channel restoration scenario 1. The oxbow channel restoration scenario 1, includes filling of the channel adjacent to the oxbow levee breaches, shows much higher velocities in this area because of the fact that flow is shallower as a result of channel filling. Again, as is the case with the upper river levee breach onto Goose Bay, velocities of flow onto the floodplain/delta through the levee breaches in the oxbow reach are of a similar magnitude to the flow velocities in the main channel for all model scenarios, with the exception of the oxbow channel restoration scenario 1, which showed greater velocities onto the floodplain as a result of channel filling.

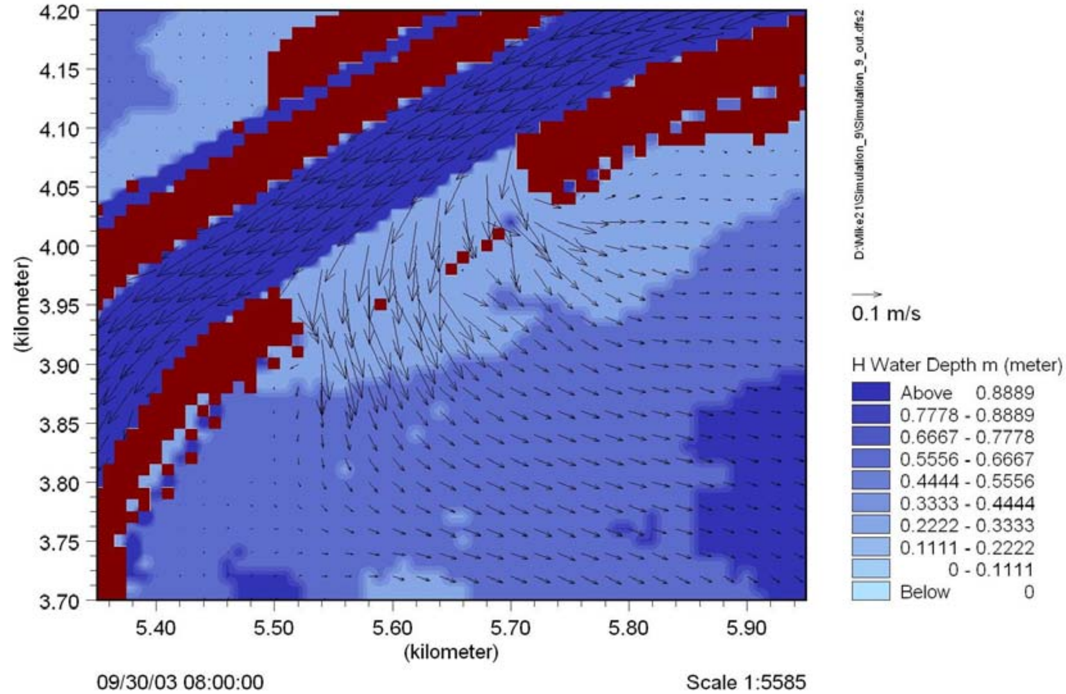

Figure 61. Velocity vector plot of the upper river levee breach and flow onto Goose Bay.

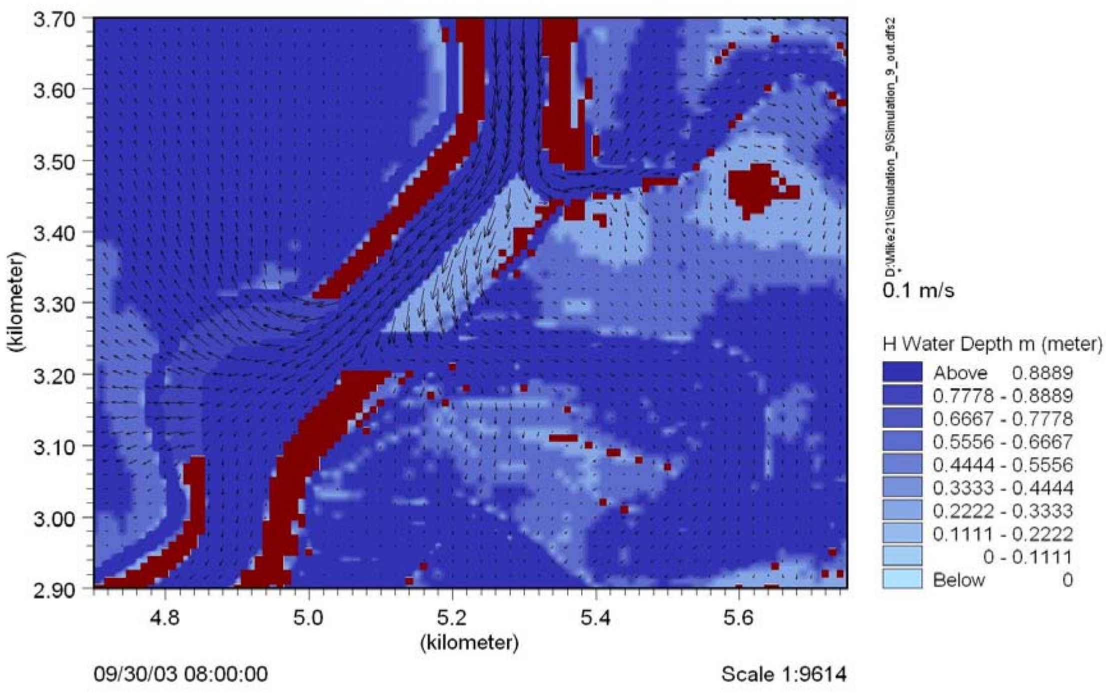

Figure 62. Velocity vector plot of the river levee breach in the oxbow area of the river and flow onto Goose Bay and Tulana.

6.3 Potential Effects of Vegetation

The hydraulics of flow across the floodplain/delta will be affected by the growth of vegetation in many areas over time due to its influence on roughness. The Manning's *n* roughness coefficient used to represent the floodplain/delta for the reference scenario was assumed to be the same as the *n* value in the channel. Since this may not be case once wetland vegetation becomes established, a sensitivity analysis was done to assess the effects of increased roughness on flow across the floodplain/delta.

Due to the complexity of vegetation dynamics, it is not possible to estimate the variability of roughness across the floodplain/delta. Therefore, the *n* value was increased in areas of elevation greater than 4141 feet. This elevation is assumed so that there will be at least some variation in roughness over the floodplain/delta. That is, if a lower elevation were assumed, the roughness over the majority of the floodplain/delta would be constant. The *n* value was set equal to 0.026 in the channel and 0.05 in the floodplain/delta. The roughness will be less along paths of higher velocity. It is also important to note that roughness may be less than the value of 0.05 that is used in the analysis here, so the effects on velocity and flow may be less than estimated below.

The model simulations show no difference in flow patterns. However, flow velocities overbank, near the river and in the floodplain/delta, decreased by approximately 25%. When the floodplain/delta roughness is the same as the main channel, the flow velocity is about 0.6 ft/s. When the roughness in the floodplain/delta is increased, the flow velocity decreases to about 0.4 ft/s. Flow velocity in the river channel is approximately 0.7 ft/s for both cases. The effects on velocity of flow through the levee breaches in the oxbow reach are not as great as in the upper river levee breach. This is due to the fact that elevations are lower near the oxbow and roughness values in the area are lower on average. There is also a decrease in the quantity of flow through the upper river levee breach onto Goose Bay. There was a decrease in the percentage total flow through the breach from 19% of total river flow (2,070 ft^3/s) to 12% of total flow. The amount of flow getting out through the breaches in the oxbow reach was not changed significantly. Figure 63 shows the percentage of total flow through breaches on the Tulana and Goose Bay sides. The decrease in flow into Goose Bay, between the results shown in figures 23 and 63, results from a reduction in flow through the upper river levee breach.

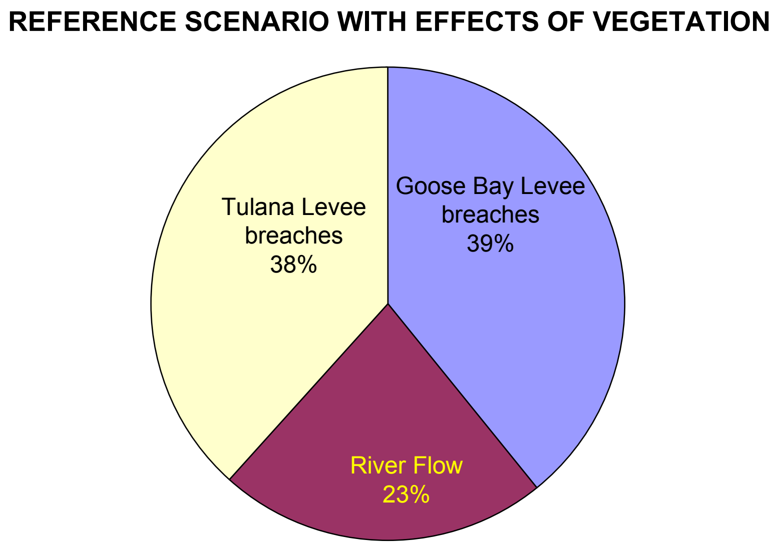

Figure 63. Flow distribution for the reference scenario with vegetation: Percentage of total river flow (2,070 ft^3/s) through river levee breaches to Tulana and Goose Bay, and the percentage of total flow through the river channel at the mouth of the Williamson River into Upper Klamath Lake.

Owing to the complex dynamics of vegetation establishment and growth, it is difficult to model the potential effects of vegetation roughness, especially over time, on flow patterns and velocities across the floodplain/delta. Roughness and resistance to flow will have its greatest effects when flow is shallow. It will tend to reduce the quantity of flow and the velocity of flow, but it will not likely have a significant effect on the patterns of flow. Once vegetation grows and becomes established, it will have a greater effect on flow patterns. However, flow patterns will also affect the pattern of vegetation establishment. Additionally, overbank flow velocities can be controlled to some degree by the size of levee breaches.

7.0 Conclusions

- The base condition and reference scenario model simulations showed that strategic levee breaches along the river and lake shorelines will reconnect the river with the floodplain. Removal of the levees results in significant out-of-bank flow under conditions associated with a high lake elevation and the 1.5 year flood, which occurs, on the average, every 2 out of 3 years. Channel geometry changes are not necessary to achieve out-of-bank flow and reconnection of the river with the floodplain/delta.
- The combination of river levee, interior levee, and shoreline levee breaches represented in the reference scenario produces flow patterns similar to those observed in the base condition without any levees. The quantity of flow that gets through river levee breaches will depend on the size of all river breaches.
- Reconnection of the historic oxbow channel is the most efficient way to restore a significant amount of the historic river channel alignment. At low lake levels, there can be a continuous surface water connection with the oxbow, with levee removal to proper

elevations. Without re-excavation of the historic oxbow channel, a continuous connection can be maintained down to a lake elevation of 4140 feet. With re-excavation of the oxbow channel down to a elevation of 4136 feet, a continuous flow connection can be maintained to this lower level. The benefits from reconnecting the historic oxbow channel can be achieved without closing off the existing main channel.

- Re-establishment of the old river mouth does not have any effect on the hydraulic conditions upstream. If done in combination with re-excavation of the oxbow channel, the river alignment would be almost completely restored to the conditions evident on the 1940-41 aerial photographs.
- It is not conclusive from the available information that the channel has been significantly widened since 1940-41. The analysis of aerial photographs from 1940-41 and 1996, by Graham Matthews and Associates (1999), shows a wide range of increases and decreases in channel width. The standard deviation of the width changes was greater than the mean width change. In addition, the 1940-41 aerial photographs lack the clarity to measure distances with precisions less than 50 feet with any degree of confidence. Extensive deepening of the channel and the resulting increase in conveyance from this activity has likely had a much greater effect than any effects of widening. Narrowing the channel would not result in a significant increase in the amount of flow through each of the levee breaches, and as such, does not appear to contribute significantly to the goal of reconnecting the river and the floodplain/delta.
- All of the modeled scenarios and alternatives would result in a decrease in the upstream water surface elevation. There is no increased risk of potential flooding upstream of proposed levee breach areas. Channel alterations undertaken downstream of levee breaches will not increase upstream flood stage.
- Flow velocities entering the floodplain are similar to the river velocities in the absence of significant vegetation. The presence of vegetation would increase the roughness and decrease both the quantity and velocity of flow. However, even with Manning's *n* roughness coefficients as high as 0.05 for the overbank areas, flow velocities were 75% of the velocities simulated with lower roughness values.

8.0 References

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Appendix — Annual Flood Peaks

Date	Peak Discharge (ft3/s)
4/27/1917	7,000
3/28/1918	2,000
4/9/1919	3,480
3/28/1920	3,230
3/13/1921	3,260
4/30/1922	4,730
4/1/1923	2,250
2/11/1924	1,700
2/8/1925	2,890
2/11/1926	1,560
4/6/1927	4,340
3/30/1928	4,490
3/25/1929	1,290
2/13/1930	1,800
4/16/1931	1,080
3/24/1932	2,680
4/9/1933	1,520
4/3/1934	1,090
4/20/1935	2,300
4/29/1936	2,680
4/19/1937	2,540
4/22/1938	7,620
3/30/1939	1,810
4/3/1940	5,550
2/16/1941	1,560
4/19/1942	2,470
4/1/1943	7,660
3/22/1944	1,300
5/29/1945	2,070
4/24/1946	3,140
2/16/1947	1,550
5/24/1948	2,310
5/23/1949	2,010
4/10/1950	1,920
4/21/1951	3,200

Date	Peak Discharge (ft3/s)	Years that peak flow is equaled or exceeded	Approximate Probability of Exceedance	Recurrence Interval (years)
1/5/1997	17,100	1	0.0116	86.00
12/26/1964	16,100	2	0.0233	43.00
2/24/1982	10,200	3	0.0349	28.67
1/27/1970	8,010	4	0.0465	21.50
4/1/1943	7,660	5	0.0581	17.20
4/22/1938	7,620	6	0.0698	14.33
4/27/1917	7,000	7	0.0814	12.29
4/13/1952	6,790	8	0.0930	10.75
2/11/1996	6,700	9	0.1047	9.56
3/6/1972	6,660	10	0.1163	8.60
2/28/1958	6,560	11	0.1279	7.82
4/14/1956	6,480	12	0.1395	7.17
4/3/1974	6,030	13	0.1512	6.62
3/13/1986	6,010	14	0.1628	6.14
3/28/1993	5,960	15	0.1744	5.73
4/3/1940	5,550	16	0.1860	5.38
4/10/1954	5,420	17	0.1977	5.06
3/14/1989	5,290	18	0.2093	4.78
3/28/1971	5,140	19	0.2209	4.53
4/4/1983	5,050	20	0.2326	4.30
4/30/1922	4,730	21	0.2442	4.10
3/2/1957	4,650	22	0.2558	3.91
4/5/1969	4,640	23	0.2674	3.74
4/23/1999	4,540	24	0.2791	3.58
3/30/1928	4,490	25	0.2907	3.44
4/6/1927	4,340	26	0.3023	3.31
5/14/1967	4,300	27	0.3140	3.19
1/17/1980	4,100	28	0.3256	3.07
3/18/1984	4,070	29	0.3372	2.97
4/10/1985	4,000	30	0.3488	2.87
5/25/1953	3,940	31	0.3605	2.77
3/28/1998	3,930	32	0.3721	2.69
2/27/1968	3,780	33	0.3837	2.61
10/17/1962	3,700	34	0.3953	2.53
5/7/1975	3,510	35	0.4070	2.46

Date	Peak Discharge (ft3/s)	Date	Peak Discharge (ft3/s)	Years that peak flow is equaled or exceeded	Approximate Probability of Exceedance	Recurrence Interval (years)
4/13/1952	6,790	4/9/1919	3,480	36	0.4186	2.39
5/25/1953	3,940	3/13/1921	3,260	37	0.4302	2.32
4/10/1954	5,420	3/28/1920	3,230	38	0.4419	2.26
4/1/1955	2,120	4/21/1951	3,200	39	0.4535	2.21
4/14/1956	6,480	1/18/1978	3,160	40	0.4651	2.15
3/2/1957	4,650	4/24/1946	3,140	41	0.4767	2.10
2/28/1958	6,560	4/23/2000	3,060	42	0.4884	2.05
1/30/1959	1,640	4/4/1966	3,020	43	0.5000	2.00
3/11/1960	2,050	4/12/1995	2,910	44	0.5116	1.95
2/14/1961	2,050	2/8/1925	2,890	45	0.5233	1.91
4/11/1962	2,810	4/11/1962	2,810	46	0.5349	1.87
10/17/1962	3,700	4/14/1964	2,720	47	0.5465	1.83
4/14/1964	2,720	3/24/1932	2,680	48	0.5581	1.79
12/26/1964	16,100	4/29/1936	2,680	49	0.5698	1.76
4/4/1966	3,020	4/19/1937	2,540	50	0.5814	1.72
5/14/1967	4,300	4/19/1942	2,470	51	0.5930	1.69
2/27/1968	3,780	5/24/1948	2,310	52	0.6047	1.65
4/5/1969	4,640	4/20/1935	2,300	53	0.6163	1.62
1/27/1970	8,010	4/1/1923	2,250	54	0.6279	1.59
3/28/1971	5,140	4/1/1955	2,120	55	0.6395	1.56
3/6/1972	6,660	5/29/1945	2,070	56	0.6512	1.54
1/16/1973	1,650	3/11/1960	2,050	57	0.6628	1.51
4/3/1974	6,030	2/14/1961	2,050	58	0.6744	1.48
5/7/1975	3,510	5/23/1949	2,010	59	0.6860	1.46
3/21/1976	1,960	3/28/1918	2,000	60	0.6977	1.43
3/25/1977	1,020	3/16/1987	1,970	61	0.7093	1.41
1/18/1978	3,160	3/21/1976	1,960	62	0.7209	1.39
5/11/1979	1,590	4/10/1950	1,920	63	0.7326	1.37
1/17/1980	4,100	3/30/1939	1,810	64	0.7442	1.34
2/19/1981	1,710	2/13/1930	1,800	65	0.7558	1.32
2/24/1982	10,200	2/19/1981	1,710	66	0.7674	1.30
4/4/1983	5,050	2/11/1924	1,700	67	0.7791	1.28
3/18/1984	4,070	1/16/1973	1,650	68	0.7907	1.26
4/10/1985	4,000	1/30/1959	1,640	69	0.8023	1.25
3/13/1986	6,010	1/11/1990	1,610	70	0.8140	1.23
3/16/1987	1,970	5/11/1979	1,590	71	0.8256	1.21
3/4/1988	1,590	3/4/1988	1,590	72	0.8372	1.19
3/14/1989	5,290	2/11/1926	1,560	73	0.8488	1.18

Date	Peak Discharge (ft3/s)		Date	Peak Discharge (ft3/s)	Years that peak flow is equaled or exceeded	Approximate Probability of Exceedance	Recurrence Interval (years)
1/11/1990	1,610		2/16/1941	1,560	74	0.8605	1.16
5/23/1991	1,140		2/16/1947	1,550	75	0.8721	1.15
12/16/1991	700		4/9/1933	1,520	76	0.8837	1.13
3/28/1993	5,960		3/27/2001	1,310	77	0.8953	1.12
3/4/1994	868		3/22/1944	1,300	78	0.9070	1.10
4/12/1995	2,910		3/25/1929	1,290	79	0.9186	1.09
2/11/1996	6,700		5/23/1991	1,140	80	0.9302	1.08
1/5/1997	17,100		4/3/1934	1,090	81	0.9419	1.06
3/28/1998	3,930		4/16/1931	1,080	82	0.9535	1.05
4/23/1999	4,540		3/25/1977	1,020	83	0.9651	1.04
4/23/2000	3,060		3/4/1994	868	84	0.9767	1.02
3/27/2001	1,310		12/16/1991	700	85	0.9884	1.01